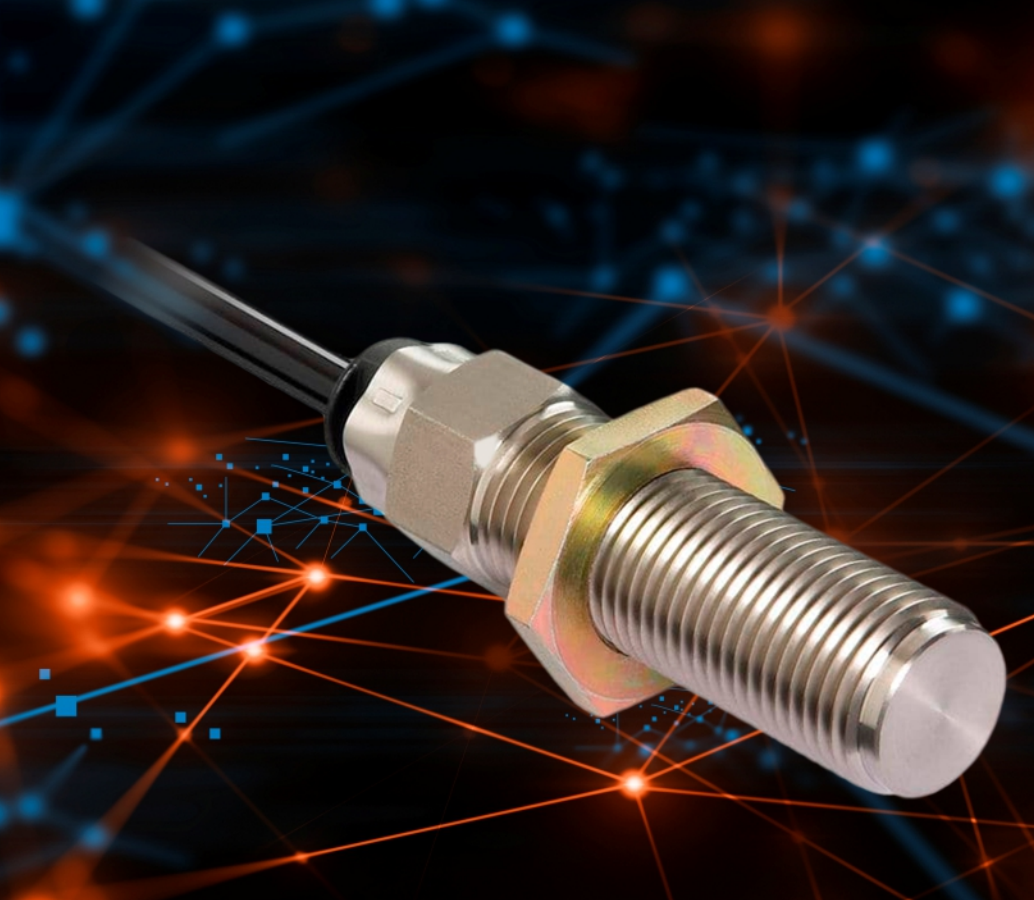


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to Artificial Intelligence**

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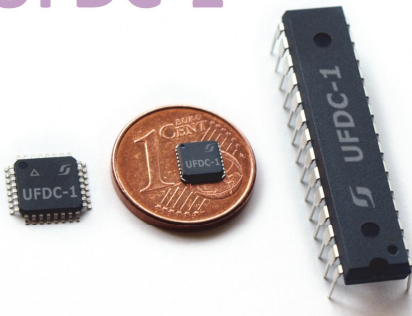
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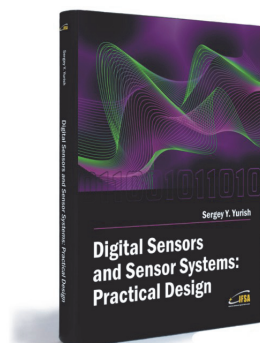


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Digital Sensors and Sensor Systems: Practical Design

Sergey Y. Yurish



The goal of this book is to help the practitioners achieve the best metrological and technical performances of digital sensors and sensor systems at low cost, and significantly to reduce time-to-market. It should be also useful for students, lectures and professors to provide a solid background of the novel concepts and design approach.

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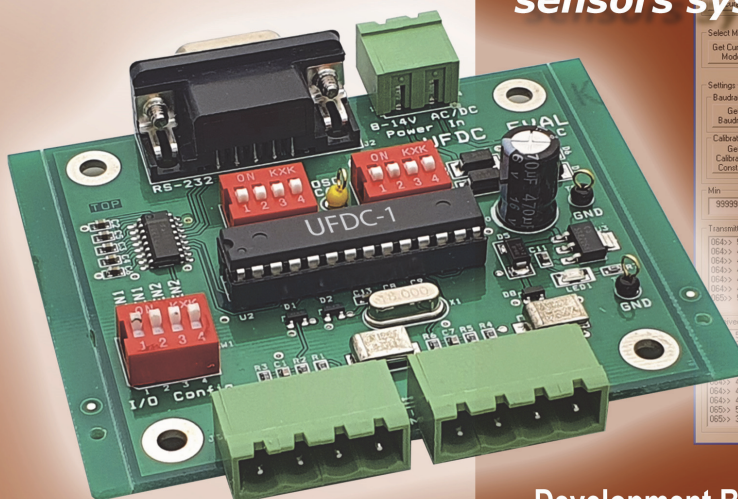
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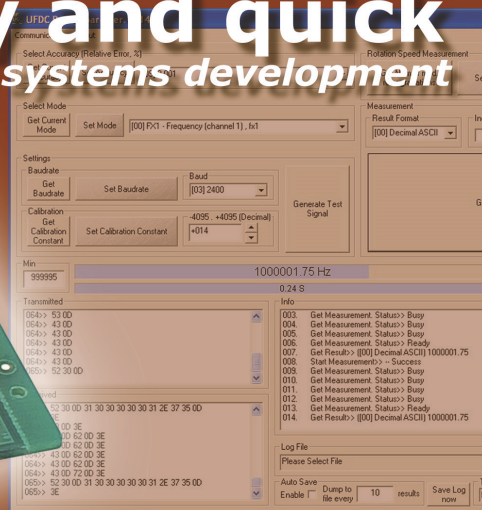
ISBN: 978-84-616-0652-8,
e-ISBN: 978-84-615-6957-1

Digital Sensors and Sensor Systems: Practical Design will greatly benefit undergraduate and at PhD students, engineers, scientists and researchers in both industry and academia. It is especially suited as a reference guide for practitioners, working for Original Equipment Manufacturers (OEM) electronics market (electronics/hardware), sensor industry, and using commercial-off-the-shelf components

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17-19 April 2024 • Funchal (Madeira Island), Portugal

ASPAI
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<https://aspai-conference.com/>

Advances in artificial intelligence (AI) and signal processing are driving the growth of the artificial intelligence market by two major factors: emerging AI technologies and intelligent signal processing. Today, more and more sensor manufacturers are using machine learning to sensors and signal data for analyses. However, the increased number of sensors in devices will inherently generate higher data throughput, which poses a serious challenge in managing and processing the tremendous amount of sensory information. Furthermore, traditional processing techniques in conventional sensing devices are no longer suitable for systematically labeling, processing, and analyzing the exuberant amount of information.

The artificial intelligence market size was US \$ 428.00 billion in 2022 and is projected to grow from US \$ 515.31 billion in 2023 to USD 2,025.12 billion by 2030, exhibiting a CAGR of 21.6 %.

The global AI market growth is driven by increasing adoption of cloud-based applications and services growing big data increasing demand for intelligent virtual assistants advances in signal processing. The major restraint for such market is the limited number of AI technology experts. Today, there are approximately several hundred thousand AI researchers and practitioners worldwide, but the market demand is around millions of roles.

The series of ASPAI conferences have been launched to fill-in this gap and provide a forum for open discussion and development of emerging artificial intelligence and appropriate signal processing technologies focused on real-word implementations by offering Hardware, Software, Services, Technology. The goal of the conference is to provide an interactive environment for establishing collaboration, exchanging ideas, and facilitating discussion between researchers, manufacturers and users.

The topics of interest include (but not limited):

Artificial Intelligence:

- AI Algorithms
- Intelligent System Architectures
- Hybrid Intelligent Systems
- Artificial Neural Networks
- Expert Systems
- Intelligent Networks
- Parallel Processing
- Pattern Recognition
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- Distributed AI
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- Multisensor Data Fusion Based on Neural and Fuzzy Techniques
- Applied Artificial Intelligence
- Self-Organising Networks

Signal Processing:

- Signal Processing Theory and Methods
- Sensor Array and Multichannel Signal Processing
- Multivariable Sensor Systems
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Submission (2-page abstract): **29 February 2024**
Notification of acceptance: **15 March 2024**
Registration: **25 March 2024**
Camera ready (4-6 pages paper): **30 March 2024**



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- Posters
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- Exhibition

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2. Authors will be invited to submit full-page extended papers to one of special journals' issues, which are published in both formats: print and electronic:
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 - Integrated Computer-Aided Engineering (ISSN: 1069-2509, e-ISSN: 1875-8835) by IOS Press
 - International Journal of Neural Systems (ISSN: 0129-0657, e-ISSN: 1793-6462) by World Scientific
3. The limited number of full-page papers published in the Sensors & Transducers journal will be selected by the Editorial Board to extend for open access books' chapters for the Book Series on 'Advances in Signal Processing', Vol. 4 or 'Advances in Artificial Intelligence', Vol. 4, which will be published by IFSA Publishing in 2024.

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Authors are welcome to propose and manage special sessions during the ASPAI' 2024 conference. Each special session will contain 4-6 papers in a related field as specified above. Session organizers will get:

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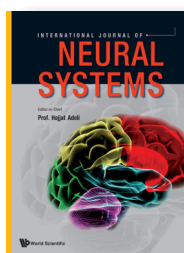
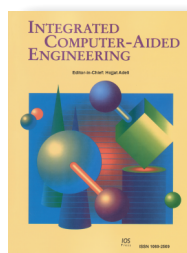
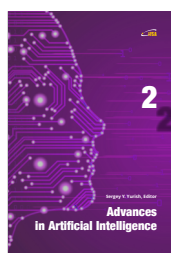
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Social Programme

Welcome Cocktail. 16 April 2024 (20:00-21:30). The Welcome Cocktail will take place in the Pestana Casino Park Hotel in the Dockside Bar with a fantastic esplanade overlooking the marina and the sea. Do not miss this opportunity to say the first "hello" to attendees and committee members.

Gala Dinner. 18 April 2024 (20:00-23:30). The Gala Dinner will take place in the the Pestana Casino Park Hotel.



Sensing the Mechanical Properties of AlN Thin Films Using Micromechanical Membranes in Combination with Finite-element Simulations

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Abstract: The current interest in quantum technologies calls for the development of novel materials and hybrid structures. Understanding the mechanical properties of a material can be a challenge, especially at the nanoscale. We use the eigenfrequencies of in-house fabricated silicon nitride membranes in combination with finite-element simulations to extract the stress in a film that is deposited on top. The high stress results in sharp resonances that can be located precisely so that the mechanical properties of the top layer can be determined accurately. We highlight this approach using aluminum nitride – an important material for on-chip quantum optics and optomechanics – grown onto these micromechanical membranes. The detection is done optomechanically by exciting the modes using a piezo actuation and detecting the vibrations in the reflected laser light. For this, different lasers are at our disposal. The resonances of a wide variety of highly stressed membranes are measured. The frequencies follow the expected inverse length dependence of a stressed membrane and depend on the thickness of the top layer. To connect the experimental observations to the material properties, finite-element simulations are used. It is shown that full simulations of the membranes are only possible for simplified geometries. When simulating the actual geometry, this, however, becomes infeasible. It is shown that simulations of a single unit cell – in particular band structure calculations – can be used to accurately model the actual structure of the membrane. Although this approach is strictly speaking only valid for infinitely large membranes, it is shown that edge effects are negligible. With the simulations, the stress in the bilayer is determined. A cross-over between compressive and tensile stress is observed as a function of the AlN thickness.

Keywords: Optomechanics, Film stress, Aluminum nitride (AlN), MEMS, Silicon Nitride (SiN), Bilayer membrane, Finite-Element Simulations (FEM), Mechanical band structure.

1. Introduction

Micromechanical membranes provide an important platform for a wide variety of optomechanical experiments. This can range from scanning force microscopy [1], to study cavity optomechanical backaction [2], the observation of

hybridization of degenerate eigenmodes [3], topological energy transfer [4], all the way to radiative heat transfer mediated via Casimir fluctuations [5]. Another important aspect of these very thin membranes is that they can be used to sense materials that are placed on top [6, 7]. This provides an interesting route to measuring the mechanical

properties of a variety of materials that can be deposited or grown on top of existing high-stress silicon nitride (SiN) membranes [8].

As will be described in detail in [8], we make membranes with and without the second layer on top and measure their eigenmodes. The dimensions of our membranes can be varied by design and typical sizes are 10s to 100s of μm in width and length. The thickness is determined by the SiN film thickness and is typically 100s of nm [3]. We illustrate that we can determine the stress in an aluminum nitride (AlN) layer grown on top of a suspended SiN membrane. AlN is an important material for the emerging field of quantum technologies, especially when photonic integrated circuits with nonlinear optics or optomechanics are involved [9-11]. Due to the used geometry of the membranes, finite-elements simulations are essential for connecting the measurements to the mechanical properties. These simulations are the main focus of this work. The samples and setup are described in Section 0. Section 0 briefly states the experimental outcomes; the simulations are the topic of Section 4. Using these Section 0 gives the resulting extracted stress in the AlN films.

2. Samples and Setup

2.1. Nanofabrication, AlN Growth and Chip Layout

Our membranes are made on chips with a 330 nm thick stoichiometric SiN layer, which is grown commercially on top of a 3.17 μm thick silicon oxide (SiOx) layer using LPCVD and has a tensile stress of about 1100 MPa. Underneath these two layers is the silicon carrier. Release holes are defined in the silicon nitride using electron-beam or optical lithography followed by reactive ion etching. The number of holes and their spacing set the size of the membrane. For this work, a single layout was used with 120 membranes with varying size on every chip, as shown in Fig. 1. The holes in the SiN layer expose the underlying oxide and by immersing the chip into buffered hydrofluoric acid (BHF), the exposed SiOx is etched isotropically, resulting in circularly expanding drums originating at the etch holes. The etching is continued until these “drums” are no longer supported by “pillars”, thus forming a fully suspended SiN membrane. The radius of the drums R is the sum of the radius of the etch hole and the underetching distance. The finite selectivity of BHF between SiN and SiOx ($\sim 1:71$) results in a uniform thinning of the top surface and slightly tapered bottom profiles of the SiN. The tapering originated from the duration a specific part was exposed to the etchant. It thus tapers from the same amount as removed from the top side at the release hole, to zero at the end of the drum, i.e. at $r = R$. This is also visible in optical reflection maps.

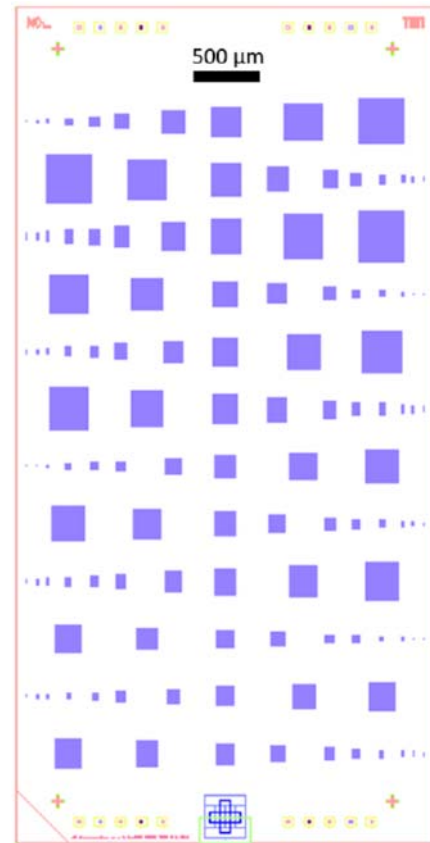


Fig. 1. Layout for a 6×10 mm chip with 120 membranes of different sizes indicated in blue. Structures for alignment, device and chip identification, and logos are indicated in red. Marker protection using SU8 is shown in yellow.

The resulting “silicon-nitride only” membranes can already be used for a variety of optomechanical experiments. In particular we have used these to demonstrate efficient mode mapping [3] – even in the presence of crosstalk [12] – and to study the spatial structure of nonlinearities.

However, here as the next step, AlN is grown on top of the membranes using DC magnetron sputtering using the process that we developed for hybrid photonic integrated circuits and which is detailed in [13]. Using X-ray diffraction, it was confirmed that these films are of good crystalline quality and have a strong c-axis orientation. Also, optical reflectometry indicates that the films have low optical losses. In addition, atomic force microscopy shows low roughness, indicating that the films are of good quality. However, accessing the mechanical properties is more difficult, and hence an important open task. For example, it is known from literature that the growth process and the final thickness influence the stress in the AlN [14]. It is thus important to have a quick and reliable method to determine the stress in the deposited film and in the resulting bi-layer membrane. Our other work [8], we will focus on the measurements and outcomes, whereas here the focus is on the more technical results, in particular on the implementation of the finite element simulations. However, before focusing on that topic, first the setup

and kind of results that are obtained are discussed to give the reader a good idea of the important aspects of the simulations.

2.2. Experimental Setup

The chips are glued onto a piezo element for actuation and mounted in a vacuum chamber as shown in Fig. 2.

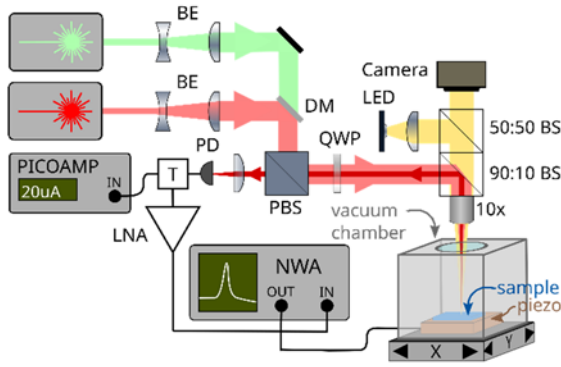


Fig. 2. Schematic of the measurement setup. Two different lasers can be used for measuring the driven response of the bilayer membranes that are mounted on a piezo actuator and placed in the vacuum chamber. For clarity, the green laser light path is not shown in full. Adapted from [3].

In short, a red HeNe laser (633 nm, Mellers Griot 05-LHP-141) is focused onto one of the membranes – or any other mechanical resonator – using a long-working-distance objective (Mitutoyo M plan apo 10x) that is located outside the vacuum chamber. The reflected light is collected via the same objective and focused onto a high-speed photodetector (Newport 818-BB-21). Since the reflection depends on the distance between the membrane and the highly reflecting Si, this provides a sensitive way to measure the local displacement of the membrane [3]. The driven response is measured using a network analyzer (HP 4396A). Typically, first overview scans are acquired and then zooms of the resonances are taken at higher resolution. From the resonance peaks, the eigenfrequencies and quality factors are obtained by fitting a harmonic oscillator (or Duffing) response to the data. This procedure is repeated semi-automatically for the different membranes on each chip. Then the next chip with a different AlN thickness is inserted and measured again, resulting in large datasets that are processed using MATLAB® scripts. Using these, the responses can be viewed, fitted, and the fit results can be studied as function of the membrane parameters. Fig. 3 shows a selection of four membranes with identical size on the four different chips. The peaks correspond to the fundamental (i.e., the (1,1) mode [3]) out of plane eigenmodes. A clear dependence on the AlN thickness

can be seen: the thicker the AlN, the lower the resonance frequency. Here it is noted that in the overviews, the driving power is relatively high and that the peaks appear somewhat distorted, but care is taken to measure the zooms of the resonances with enough resolution and low enough excitation so that the frequencies can be determined precisely from the linear response (or slightly nonlinear response; in that case a Duffing-response fit is used).

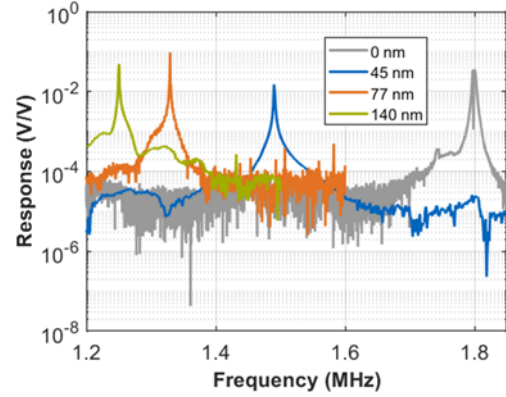


Fig. 3. Driven response near the fundamental eigenfrequency for the nominally-same membrane on different chips with different AlN thicknesses. The AlN layer clearly shifts the resonances to lower frequencies.

The readout always works well for SiN-only membranes, but for bilayer membranes with different AlN thicknesses it is possible that the derivative of the reflectivity with respect to the displacement vanishes. Hence, alternatively a green (532 nm; OneFive Katana) and even a violet laser (405 nm, not shown) can be used to sense the motion. Fig. 4 compares reflectivity maps for two laser wavelengths and two chips with different AlN thicknesses. The differences in contrast between the membrane and support are clearly visible. The different lasers (see Fig. 2) allow selection of the best color for the optomechanical readout. Also note how the small conical tapering of the membrane bottom is clearly visible in these reflection maps.

3. Resonance Frequencies

The driven response is measured for all 480 membranes (120 membranes with varying size per chip as shown in Fig. 1; 4 chips with different thicknesses t_{AlN}). The fundamental eigenfrequencies of the same membrane on four different chips were plotted in Fig. 3; from zooms the exact resonance frequency is determined and this is plotted against the size of the membrane in Fig. 5. The strong variation of the frequency with membrane size makes it beneficial to convert the frequency to the speed of sound for the flexural vibrations, which – for an idealized membrane – equals the square root of the thickness-weighted sum

of the stress and mass density of the bilayer. Specifically, the effective membrane size is given by:

$$L_{\text{eff}} = \left(\frac{1}{L_x^2} + \frac{1}{L_y^2} \right)^{-1/2}$$

This means that L_{eff} tends to the smallest of the two side lengths, that is when $L_x \gg L_y$, L_{eff} equals L_y and vice versa. For a square membrane $L_x = L_y$, and $L_{\text{eff}} = L_x/\sqrt{2}$. The question what the exact side length is when the membrane consists of individual drums, will be addressed in Section 4.3. However, the bottom line is that $2L_{\text{eff}}f_{(1,1)}$ equals the speed of sound c . The speed of sound is thus a central quantity that can be determined from the experiments, calculated analytically, and also simulated [8][8]. It contains the material properties of the bilayer, specifically the stresses in the two materials. Hence, with the known properties of the SiN layer, the stress in the AlN film can be extracted. In practice, the membrane has a complex geometry [8, 15]. This means that for the required precision, finite element simulations are used to connect the speed of sound to the material properties, in particular the thickness dependence of the stress in the AlN thin film. This will be detailed in the following section (Section 4).

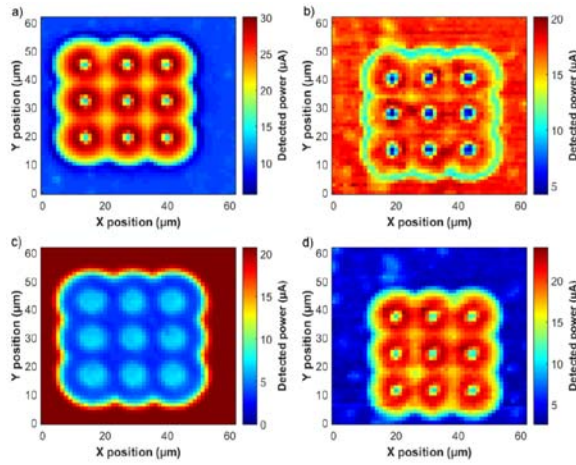


Fig. 4. Reflectivity maps for a 3×3 membrane. The top (bottom) row is taken at 633 (532) nm. The left (right) column has 77 (140) nm of AlN grown onto the suspended silicon nitride membrane [7].

4. Finite Element Simulations

In this section, we describe how the finite-element simulations for connecting the experimentally determined quantities to the parameters of the top layer. Like for the simulations of our stressed pre-displaced string resonators [16] also here the FEM simulations of our structures were initially built with the graphic user interface of COMSOL MULTIPHYSICS® (versions 5.3 to 5.6 were used

throughout the project). To sweep parameters, and to extract and process results, the simulations were controlled with our simulation framework written in MATLAB®. For this integration, the COMSOL model was exported as a script and edited to the specific needs. Then the scripts were run via the COMSOL's LiveLink for MATLAB™ on regular personal computers (PCs) with Windows 10. Most of the simulation in this paper were run on a PC with 32 GB memory and an Intel® i7 13700 processor.

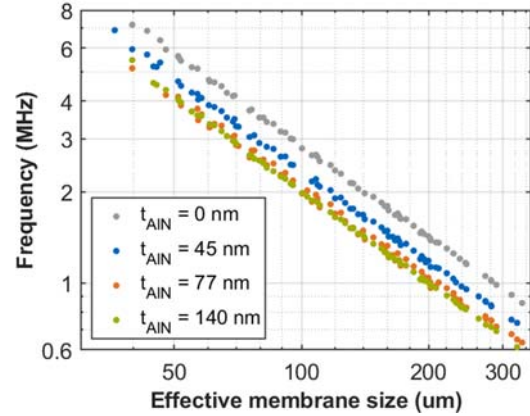


Fig. 5. Measured fundamental resonance frequency $f(1,1)$ for membranes of different size with different amounts of AlN on top. The slope of -1 in this log-log plot indicates that $f(1,1) \propto 1/L_{\text{eff}}$ i.e. that the membranes are stress dominated. Their slope is twice the speed of sound.

4.1. Building the Model

As a first step, the geometry is defined (i.e. a bilayer rectangular membrane, membranes composed of drums, or an individual drum/unit cell, depending on the exact simulation as will be discussed in the next Sections) and Si_3N_4 from the material library is applied to the bottom layer. For the top layer – i.e. the AlN – the mechanical properties are set manually.

Next, the film stresses are added via the initial stress and strain under *linear elastic material* by setting $\sigma_{xx} = \sigma_{yy} = 1105.1$ MPa and $\sigma_{zz} = 0$ for the SiN [16]. The stress in the AlN is set similarly and is varied as a parameter passed by the MATLAB control script. For the full simulations (Sections 4.2 and 4.3), the boundary conditions for the sides are set to the *fixed constraint*. For the band structure simulations (Sections 4.4-4.6) these are set to *symmetric* for the static simulation and *period boundary conditions* are used to find the eigenmodes. Specifically, the *Floquet periodicity* boundary conditions are used and the x and y component of the wavevector $\mathbf{k}$ are specified: k_x, k_y .

The next step is to build the mesh and different coursenesses can be set. Besides the geometric and material properties, also the mesh coarseness is controlled by the simulation framework so that the influence of the mesh can be studied in detail (see e.g. Section 4.5). In general, one can expect that a finer mesh gives more accurate results at the expense of

longer runtime and memory usage. After the model is set up, it can be solved. This has two steps: First, the stationary solver is used to obtain the relaxed structure, followed by the eigenfrequency solver. One thus has access to both the results from the static relaxation (deformation, stresses), as well as for the dynamics around this relaxed geometry (eigenfrequency, modal displacement, ...).

4.2. Full Simulations

The better the simulations reflect reality, the better the agreement should be – at least in principle as there is often a trade-off between detail level, accuracy, and the required computation resources. Still, it makes sense to first see what a full simulation gives. Fig. 6 shows the calculated fundamental frequency $f_{(1,1)}$ of rectangular SiN-only membranes with varying aspect ratios, i.e. ratios between their length L_x and width L_y . For large sizes – say, $L_{\text{eff}} > 100 \mu\text{m}$ – the membranes are tension dominated and when using the effective length defined above, the frequency in this domain is fully described by the speed of sound.

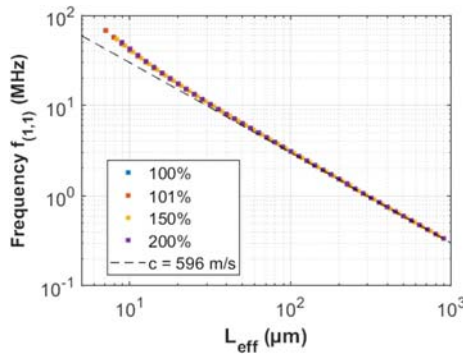


Fig. 6. Simulated fundamental resonance frequency of ideal rectangular SiN-only membranes of different sizes and aspect ratios L_x/L_y . After converting the sizes to the effective length, all curves collapse onto a single line. For large membranes, this matches the frequency calculated for a membrane under tension with a constant speed of sound $c = \sqrt{\sigma/\rho}$ (dashed line). The thickness of the silicon nitride is 330 nm in these simulations.

The next step is to see the influence of the AlN layer on top. Similar to the experimental observations of Fig. 3, Fig. 7 shows that when the thickness of the top layer increased, the speed of sound in the tension-dominated range decreases – and, thus, $f_{(1,1)}$ with it.

This can be seen in two different ways (note that the mass density of SiN and AlN are very similar):

1. The mass per unit area (in kg/m^2) of the membrane increases with the same amount of tension (in N/m);
2. The mass density (in kg/m^3) remains similar, but the average stress (in N/m^2) decreases.

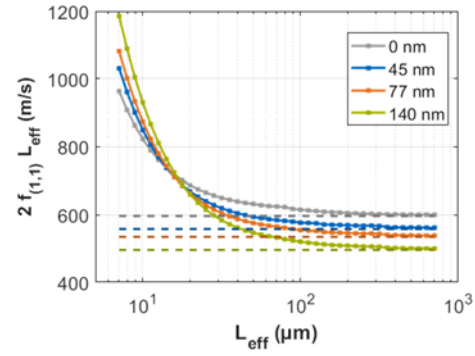


Fig. 7. Simulated frequencies for the fundamental mode multiplied by twice the effective size of square membranes with varying size. The dashed lines indicate the speed of sound as thickness-weighted average of the two layers. colors indicate the different thicknesses of the top layer. In this simulation the thickness of the silicon nitride is 330 nm and the stress of the AlN is 0.

Both ways are understood from a simplified model where the speed of sound is the thickness-weighted average of the density and stress in the two layers [8]. The simulations converge to this value (dashed lines) for large effective sizes. Also visible is that the crossover to the bending regime moves to slightly larger membranes for thicker AlN as the bending rigidity is proportional to the total thickness to the power 3 [17]. There, the thickest layer of 140 nm also has the highest speed of sound. We note again that the actual structure of our membranes is more complex than a simple uniform rectangular membrane. In particular:

1. There are periodically arranged etch holes in the SiN, where the in-plane stress can partly relax;
2. The finite selectivity partly removed the SiN, resulting in cone-like structures at the bottom. The thickness of SiN is thus reduced below the initial nominal value of 330 nm and varies with the location;
3. The fact that the membrane constitutes of individual drums implies that the sides have “wavy” instead of straight edges.

Full simulations of small membranes taking all these elements into account are feasible, but for larger sizes this soon results in excessive simulations duration or required resources as shown in Fig. 8. Membranes with thin AlN layers and all features take the longest; simple SiN-only membranes (dark blue color) are the fastest (e.g. when simulating the results for Fig. 6 and Fig. 7) as there are no small features in the plane. Still, the simulation time increases roughly exponentially with the drum number. This means that simplifications have to be made. We will first address the third point in the next section (4.3) and with the findings there, it is shown that the other two points can be tackled using band structure simulations (Section 4.4). Note that for membranes made from a small number of drums the modes may be different from the modes of a rectangular membrane under tension, where: $u_{m,n}(x,y) \propto \sin(\pi m x/L_x) \sin(\pi n y/L_y)$ [3].

In particular for $N_x = N_y = 1$ the membrane is just a single circular drum where – in the tension dominated case – the eigenmodes are given by Bessel functions instead of sine functions [18]. There it is commonplace to also label the modes with two integers in round brackets, giving the number of nodes in the angular and antinodes in the radial direction, respectively. In the following we usually label the modes with a single number i that indicates the ordering. f_1 is thus the lowest (i.e. fundamental) mode of every membrane and would correspond to $f_{(1,1)}$ for a rectangular membrane and $f_{(0,1)}$ of a circular one.

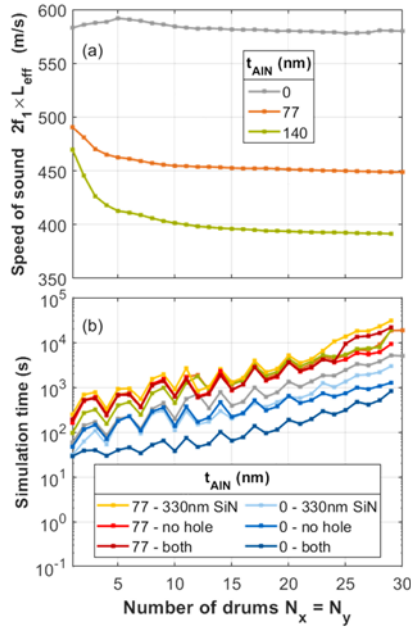


Fig. 8. Full simulations of membranes with varying number of drums. (a) shows the duration of each simulation. (b) Speed of sound for three different thicknesses. The other lines in (a) show the influence of several features, such as no removal of SiN, no release hole or both. The order of the simulations varied, resulting in a wavy pattern. $R = 11 \mu\text{m}$ and $A = 14.56 \mu\text{m}$. 330 nm SiN with 140 nm removed unless mentioned otherwise.

4.3. Influence of the Drums at the Edges and Corners

As can be seen in e.g. the reflection maps from Fig. 4, the outline of the membranes is not a perfect rectangle as it is made from a discrete number of overlapping drums. The impact of this is studied using simulations in this Section. For this, pure silicon nitride membranes without etch holes are simulated. The thickness was kept constant at 330 nm, so that the impact of the other two points from Section 4.2 do not play a role and the edge effects can be isolated. Fig. 9(a) shows the simulated fundamental resonance frequency where the outer dimensions $L_x = L_y$ were kept fixed, but the number of holes was varied (keeping $N_x = N_y$). Since $L_{x,y} = 2R + (N_{x,y} - 1)A_{x,y}$ this means that the lattice constants $A = A_x = A_y$ thus varied

with the number of drums to keep the size the same. The overlap $2R - A$ thus increased and the insets show that the larger the number of drums, the smoother the edges appear. The simulated frequencies are higher for small numbers and tend to a limiting value for large numbers. Note that for $N_x < 12$, the membrane would not be fully suspended as $A_x^2 + A_y^2 > 4R^2$, i.e. that the aforementioned “pillars” remain. Hence these points are not included in the plot. The solid lines indicate the frequency estimated using the speed of sound $c = \sqrt{\sigma/\rho}$. In this case, either the outside (red), or the inner side (green) length is taken to calculate the effective membrane size. In the latter case one obtains:

$$L_{\text{eff}} = \left(\frac{1}{(L_x - 2\Delta L_x)^2} + \frac{1}{(L_y - 2\Delta L_y)^2} \right)^{-1/2},$$

where $\Delta L_{x,y} = R - \sqrt{(R^2 - A_{y,x}^2/4)}$. It is clear that the corrected effective size describes the increase with reduced drum number reasonably well. The small offset of about 50 kHz is attributed to the remaining bending rigidity of the flat 330 nm-thick membrane. This shows that irrespective of the “wavy” edges, the frequency is still given by $c/2L_{\text{eff}}$ as long as the right dimensions are used in the analysis. Still, the finite radius of the drum in the four corners may also influence the results. This is studied in **Error!**

Reference source not found.(b).

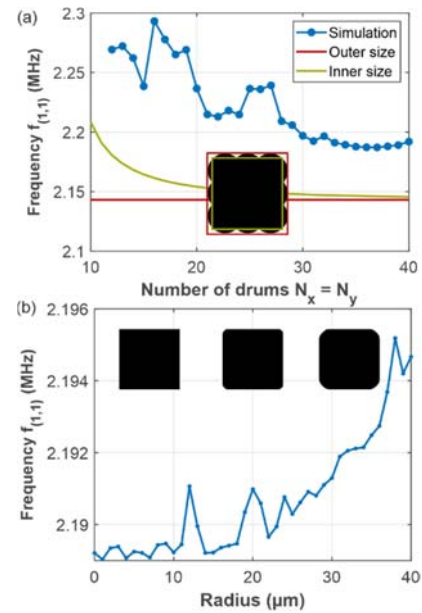


Fig. 9. Simulated fundamental frequency of SiN-only membranes consisting of an $N_x \times N_y$ array of drums (a). The drum radius was $11 \mu\text{m}$, but etch holes were not included as explained in the text. The solid lines show the frequency estimated using the speed of sound and the effective length determined from the outer size (red) and the inner size of the membrane (green) as shown schematically in the inset. (b) Rectangular membrane with rounded corners as illustrated in the insets. In all simulations in this figure, the outer side length was kept at $196.7 \mu\text{m}$.

Here, again 330 nm flat SiN-only membranes without etch holes are simulated. Now, the edges are kept straight, but the corners have a varying “fillet” radius R . A perfect rectangular membrane would have $R = 0$, but experimentally, we have $R = 11 \mu\text{m}$ (1 μm due to the release hole, plus 10 μm due to the lateral etching). Fig. 8(b) shows that in this case, the correction is very small ($\sim 10^{-4}$). This thus shows that the effect of the non-straight edges and corner radius can thus be neglected in the experimentally-relevant geometries.

Finally, it was found that the *virtual operation* to ignore the internal boundaries between the overlapping drums when meshing the structure resulted in a significant speedup, without which the simulations in this Section would have taken unreasonably long.

4.4. Unit Cells vs Full Simulations

As we argue in [8], the fact that the membranes consist of periodically-repeating structures of etch holes and “cones” due to the nonuniform etching of the bottom side where the etch holes are located at a square lattice means that an infinitely large membrane can be described fully using band structure calculations of individual unit cells. Although we showed in Section 4.3 that the edges do not significantly impact the resulting eigenmodes – at least not when using the correct dimensions, it is not a priori clear if the band structure calculations can also be used to accurately model membranes of finite size.

In this case, the speed of sound is given by ω_i/k which becomes $c = 2f_1 \times \pi/k$ for the fundamental mode. This relation connects the magnitude of $\mathbf{k}$, i.e. k , to effective size of the membrane $L_{\text{eff}} = \pi/k$. Although it was shown in [8] that the direction of $\mathbf{k}$ is not relevant for the fundamental mode – a statement that will be discussed further in the next section, this could be taken into account by evaluating the frequencies for $k_x = \pi/L_x$ and $k_y = \pi/L_y$. However, this would imply that again every membrane geometry has to be simulated. Right now, only a single value for $\mathbf{k}$ suffices for each unit cell (corresponding to 30 membrane), significantly speeding up sweeps of parameters (e.g. the AlN film stress in Section 4.6).

The results are presented in Fig. 10. In comparison to the full simulations, there is a clear deviation at small sizes, where the bending rigidity becomes apparent. Although the bending of the unit cell itself is taken into account (causing the increase at very small L_{eff}), this is not true for the bending due to the clamping at the edges as the band structure calculations assume an infinitely extending lattice. Still for large membranes this should not too important and both the full and unit cell simulations show – a slightly different – converging value. Future work will need to determine the origin of this shift of a few m/s. Interestingly, the unit cell simulations do approach the value $\sqrt{\sigma_{\text{avg}}/\rho_{\text{avg}}}$ so the deviation is more likely to be in the full simulations instead of the unit cell ones. A

technical point is that for the “ideal” SiN-only and square membrane with AlN there is no true periodicity (it is a uniform rectangle) so that one is free to impose any value (here, also $A = 14.56 \mu\text{m}$ is taken), a bit in analogy to the empty lattice calculations of free-electron band structures in solid state physics [19]. Note that the single full simulation (gold) at $L_{\text{eff}} \sim 300 \mu\text{m}$ took more than 5h to complete (same data as the orange curves in Fig. 8) whereas for the unit cells it was only about 3 min.

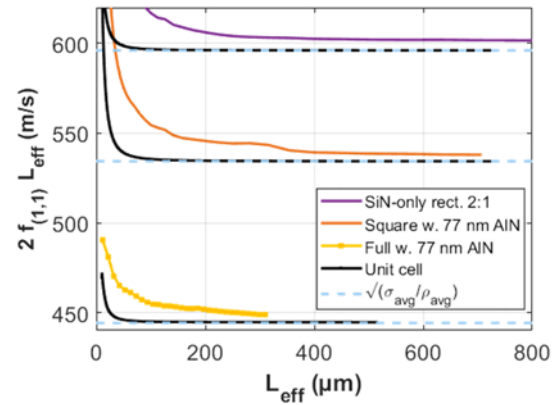


Fig. 10. Speed of sound calculated using unit cells compared to full simulations in three cases: a rectangular SiN-only membrane (cf. Fig. 6), a square membrane with 77 nm AlN and 330 nm SiN and a full membrane with 77 nm AlN (cf. Fig. 8). For large sizes, the curves approach a constant value, which for the unit cell calculations coincides with the respective values of $\sqrt{\sigma_{\text{avg}}/\rho_{\text{avg}}}$ (dashed lines).

4.5. Role of Clamping and Global Constraint

For the full simulations (Sections 4.2 and 4.3), it is clear what the boundary conditions are. However, for an infinitely repeating unit cell, the periodic boundary conditions for the static solution imply that the any solution plus a uniform displacement is still a solution and an error is raised when running the simulation. Thus, there must be an additional constraint to fix the overall displacement. For this, an “anchor” point at the rim of the etch hole is set to zero displacement for the static simulation. This additional constraint is disabled when running the eigenmode solver as there the Floquet boundary conditions remove the ambiguity in the solution. Fig. 11 shows the influence of the anchor point on the resulting first three eigenfrequencies. Note that the unit cell belongs to the C_{4v} point group and that the frequencies should thus be periodic every 90 deg. when varying the direction of $\mathbf{k}$. Any pure 180-deg. periodicity signifies a difference between X and Y that is not present in the geometry and must thus be due to the artificial additional constraint.

The second eigenmode f_2 – a transverse mode – shows a very pronounced 90° periodicity, without any sign of pure 180° components. Changing the location of the anchor does not give different frequencies (the blue curve is hidden underneath the orange one). This

mode thus depends on propagation but does not “feel” the anchor. The situation is reversed for the fundamental mode. Here there is a clear pure 180° trend that flips with a change in the anchor position, both are a clear indication of the influence of the anchoring. Still, the mode itself does not depend on the direction of the wavevector $\mathbf{k}$. Moreover, even though there is an effect visible, the difference between the two curves for f_1 is only 0.21 % so this is negligible in practice. As an alternative it is also possible to apply global “weak” constraints, e.g. that the displacement averaged over the entire geometry is zero. However, as shown in Fig. 12, this does result in a huge increase in the computation time, without any significant change in the final frequency. Hence the anchor (at the location of the blue point) will be used in the following.

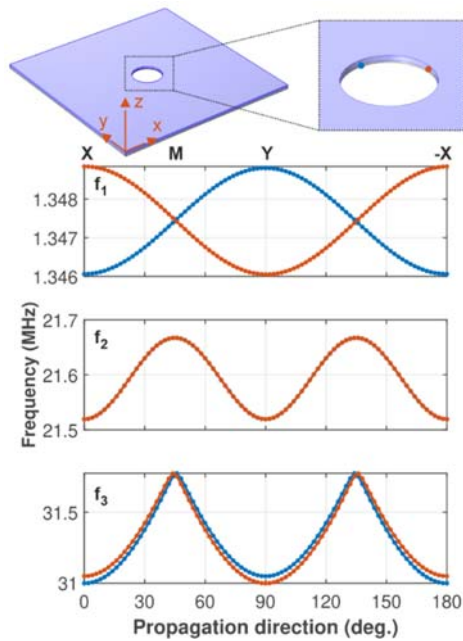


Fig. 11. Influence of the anchoring point for the static simulation of the unit cell. First three eigenfrequencies for different directions of the wavevector $\mathbf{k}$. Its magnitude was $k = 2.24 \times 10^4 \text{ m}^{-1} = 0.104 \pi/\lambda$. The blue and orange curves are for anchoring points as indicated with the same colors in the inset top panel.

4.6. Stress Distribution

Now that the validity of the simulations has been verified, a closer look at the outcomes can be taken. Of course, the main interest are the frequencies, from which the speed of sound can be obtained $c = 2f_i \times \pi/k$. Then this can be done while varying parameters of the unit cell (AIN thickness, lattice constant, ...) and material properties – in particular σ_{AIN} . This can then be used to determine the latter from the experimental observations [8] as will be summarized in Section 5. Still the simulations allow access to other quantities that are not easily accessible in the experiment, in

particular the stress tensor components and their distribution throughout the structure (cf. bilayer unit cell). To illustrate this, we simulated the static relaxation of a typical unit cell and show the results in Fig. 13 and Table 1.

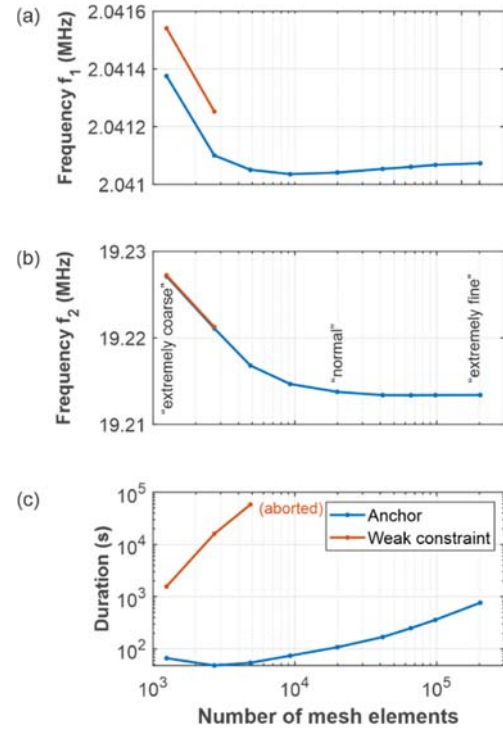


Fig. 12. (a, b) Evolution of the frequency of the first two modes and simulation time (c) for different fineness of the mesh. In the COMSOL GUI these correspond to the choices between “extremely coarse” and “extremely fine” as indicated in (b). In every panel, the two curves correspond to the anchoring (blue) and weak constraint (orange) method as detailed in Section 4.5. The latter is much slower and shows a worse scaling with number of elements, whereas there is no significant change in the final frequency. Note the very small relative span in (a) and (b). Simulation w/o AIN.

Table 1 shows the different cartesian elements of the stress tensor σ_{ij} averaged over the different parts of the membrane. It is clear that both the z ($i, j = 3$) and shear components ($i \neq j$) remain small. Also, the stresses remain largely isotropic and that there only a small amount of relaxation from the initial values for the film stresses took place. Given this, we focus on the principal stresses $\sigma_{1,2,3}$ (i.e. the ordered eigenvalues of the matrix that represents the stress tensor in a fixed coordinate system, where σ_1 is the largest [20]) instead of the cartesian components as these will better reflect the symmetries of the structure. The first two are visualized in Fig. 13. Interestingly, the anchoring point shows a larger stress, but from the discussion in Section 4.5 it is clear that this does not influence the results. Overall, one can see that at the bottom of the

SiN layer, the stress is slightly reduced as the cone-like removal of the SiN starts at the etch hole in the center leaving slightly thicker protrusions at the corners where the stress can somewhat relax (orange). This nonuniform stress leads to a ~ 100 nm downward bending of the membranes at the location of the holes. It would be interesting to see if this is the reason of the gradient of the optical reflectivity near the holes (see e.g. Fig. 4), that this is due to the tapered thickness profile, because of optical effects due to the finite spot size and/or depth of focus of the setup, or a combination thereof.

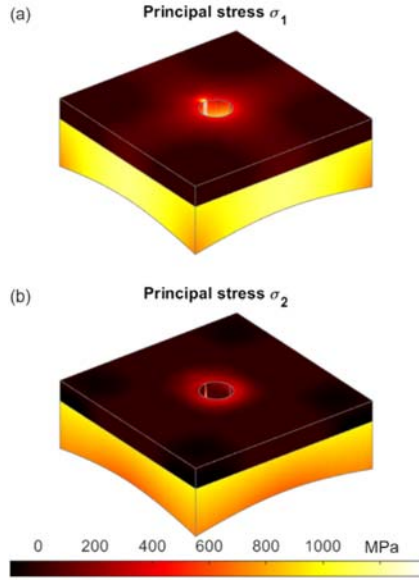


Fig. 13. Distribution of the stress after relaxation (static simulation) throughout the unit cell with $A = 14.56 \mu\text{m}$. The original SiN thickness of 330 nm is reduced by 140 nm from the top and bottom (conical) and the top layer is 77 nm of AlN. The initial film stresses were 1101.5 MPa for SiN and 0 MPa for AlN. The z axis is scaled $10\times$ for visibility. Panels (a) and (b) show the first and second principal stress, respectively. Note that $\sigma_3 \sim \sigma_{33} \sim 0$.

Table 1. Elements of the stress tensor averaged over the bottom layer (SiN), the top layer (77 nm AlN) or over the entire unit cell after the static relaxation from the simulation shown in Fig.. The initial film stresses were 1101.5 and 0 for SiN and AlN, respectively. All stresses are given in MPa and rounded.

	σ_{11}	σ_{22}	σ_{33}	σ_{23}	σ_{13}	σ_{12}
SiN	1045	1048	0	0	0	0
AlN	-6	-3	0	0	0	0
Avg.	624	627	0	0	0	0

Finally, the influence of the film stress is studied as is shown in Fig. 14. As expected, the average stress in the membrane increases when the stress in the AlN film increases. There is also a dependence of the lattice constant. The smaller A , the lower the average stress. In this case, more SiN is removed as the overlap is larger and also the impact of the holes, where the stress

can partly relax, becomes stronger. This trend is also visible in the calculated speed of sound. Over the whole parameter range, the speed of sound is accurately represented by the square root of the final average stress and the density (dashed lines). These simulations can then be repeated for different AlN thicknesses and then compared to the experimental observations.

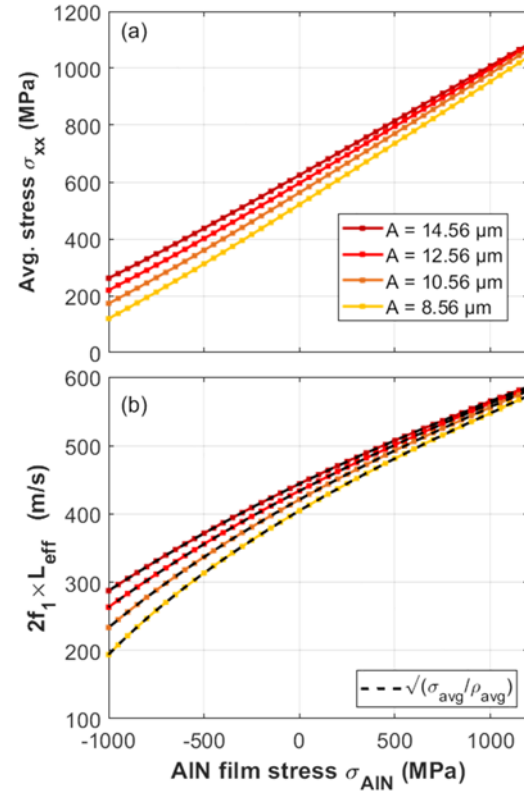


Fig. 1. Dependence of (a) the average in-plane stress (only σ_{xx} is plotted; σ_{yy} is indistinguishable) and (b) speed of sound for varying AlN films stresses. The different colors indicate the different lattice constants used in the experiments. The dashed lines give the predicted c based on the average stress (xx component as in (a)) and density (mass of the unit cell divided by its volume). The AlN thickness was 77 nm and 140 nm of the 330 nm SiN was removed.

5. Thickness Dependence of the AlN Film Stress

The data in Figs. 3 and 5 showed a clear dependence on of the resonance frequencies on the AlN thickness and with the finite element simulations that were described in detail in the previous section, this can be now analyzed quantitatively. The analysis is described in detail in [8][8], but here the final results are presented. Fig. 15 shows the stress in the AlN thin film as a function of the thickness. Interestingly, it shows that the stress transitions from compressive to tensile. We believe that this is due to the complex growth of AlN on SiN [7] and a finer sweep of the film thickness will be done to study this in more detail.

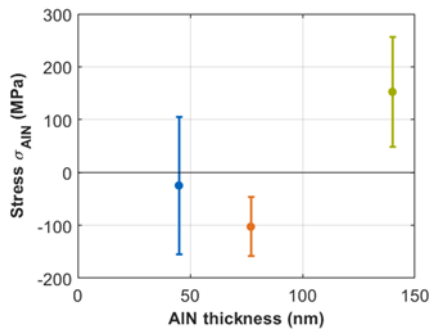


Fig. 15. Extracted stress in the AlN film σ_{AIN} vs the thickness t_{AIN} . The errorbars represent the fit uncertainty as returned by MATLAB's fit function.

6. Conclusions and Outlook

As proof of principle, we have used our SiN micromechanical membranes to determine the stress in AlN thin films that were grown on top. Finite element simulations are essential to connect the measured resonance frequencies to the mechanical properties of the membranes. The reason is that the membranes are more complex than a perfect rectangular membrane under tension. The used geometry, however, has the benefit of simple interferometric readout of the motion. It is shown that full simulations are very expensive so simplifications have to be made. It is shown that the wavy edges and rounded corners do not play an important role, at least not when the right dimensions are used for the effective length. The release hole and conical profile can be captured by band structure calculations. For the static relaxation, the role of an additional anchoring point vs a global constraint is studied. The latter – although more reflecting reality – did not improve the results, and resulted in a dramatic increase of the computation time. With the verified simulations, the stress distribution and dependence on the film stress were studied. This allowed extraction of the stress in the AlN from the experimental data. Although here we focused on AlN, our method is not limited to this material, as in principle any (semi-) transparent material may be sensed. With slight changes to the optical setup (specifically: heterodyne detection), even that requirement may be lifted in the future. The method is thus applicable to any transparent or reflecting thin film that can be grown onto our suspended SiN membranes. Further improvements will include damping and also smaller structures so that besides the stress also other mechanical properties such as the Young's modulus can be determined. Also here, we expect a strong synergy between the experiments and the finite-element simulations.

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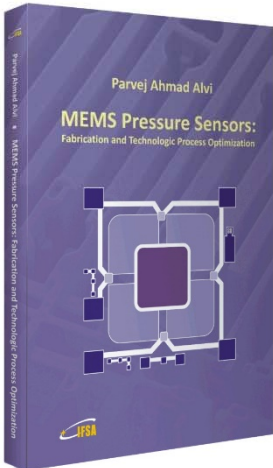
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Parvej Ahmad Alvi

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Feature Value Classification Based on the Position Difference of Pressure Sensors Installed in Insoles and Their Outputs

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Abstract: This study focuses on the sensor position in an insole system that aims to detect changes in physical conditions. To reduce the costs, the number of pressure sensors is limited to four. The system evaluates the changes in the load applied to each sensor on the insoles. Commercially available insoles are classified into S, M, and L sizes and cut to fit the shoe size. Consequently, sensors are not always attached at appropriate positions on the insole, and substantial variations are expected to occur because of misalignment. The output characteristics differ significantly depending on the toe sensor position. In particular, the toe length varies considerably among individuals, and the sensor position must be adjusted to suit each individual. The peak value of the sensor output and the steepest slope value at the subsequent decrease are promising feature values. The incorporation of machine learning into the output results, including other sensor positions, is expected to yield more accurate data.

Keywords: Pressure sensors, Insole, Health condition change, Arduino, Bluetooth, Classification, Machine learning.

1. Introduction

Rapid aging is a global problem [1-3] that is expected to become a major societal concern not only in Europe [4] but also in Asia [5]. The number of caregivers for the older adults is expected to increase owing to the declining birth rate, and the number of caregivers for each elderly person is expected to decrease, resulting in the elderly being cared for by the elderly. One primary concern in caring for older adults

is that they may become bedridden because of fractures caused by falls.

Several studies have used images and sensors to prevent falls [6-13]. Insole sensors [14, 15], which are commercially available and relatively easy to use, are often used to prevent falls because the gait state is significantly influenced by physical conditions. Whereas these commercial insole sensors were mainly developed for athletes, they have attracted considerable interest because of their relevance to

lower limb dynamics that is crucial not only for runners but also for people of all ages. Furthermore, the interest in gait analysis within rehabilitation centers and facilities dedicated to the elderly is increasing.

We previously reported a sensor that was used as a reference for determining movement limitation states using data from the insole sensor pressure distribution [16-19]. The e-rubber smart insole, known as FEELSOLE®, was available in three sizes (S, M, and L) with 2 cm increments. In this case, the output of the toes appeared low that raised the question of whether accurately determining the sensor position was important. Because the tip of each toe has a short bone, a slight difference in the sensor ground position may affect the output. For certain diseases and disorders, the information from the toe portion of the insole is important, including hammertoe, a condition in which the toes are bent. The conditions under which the sole of the foot touches the ground and the pressure distribution on the sole at the start of the gait vary depending on the condition of the lower limbs. The heel, in particular, is the most pressured area, and the changes in pressure at the start of the gait are considered parameters that characterize gait and are important in the analysis.

Therefore, we fabricated a device in which a pressure sensor was fixed to the shoe insole using tape to allow the position of the sensor to change arbitrarily. Using this insole, the pressure changes during walking were examined by changing the toe sensor position, and the effects of different sensor positions were investigated.

The research was approved by the Ethics Committee of Teikyo University of Science.

2. Experiment

The pressure distribution screen of a commercially available smart insole shows the pressure applied to the sensor in different colors. In an initial experiment to determine the optimal sensor position, the sensor was placed, as shown in Fig. 1(a), using an Interlink FSR-402 sensor to obtain the foot pressure distribution for comparison with a simplified display. The sensors were affixed to four locations: 15 mm from the toe, 60 mm from the inside and outside of the foot, and 20 mm from the heel. The side with the affixed sensor was positioned downwards. As the experiment progressed, as shown in Fig. 1(b), measurements were obtained by changing the sensor placement position to 80 and 90 mm for the inner and outer sensor positions, respectively. This adjustment aimed to achieve a more accurate distribution of foot pressure. As shown in Fig. 2, the system used an Arduino Nano to convert the analog signals from the sensors into a digital format and sent them to a PC via Bluetooth using a Microchip SBD with PIC24FJ64GB004. The received signals were processed using a program created by processing, and the files were saved. For comparison, smart insole FEELSOLE® was used on top of the

fabricated insoles. The output of the homemade insole sensor was approximately 0.5 V lower because of the cushioning effect of the smart insole. A 9 V battery was used for this prototype owing to the unavailability of a polymer battery charger during the prototype phase owing to supply shortage. A self-made insole sensor was attached to the right foot for the measurements. First, sandals were used instead of shoes, this facilitated easy wiring of sensor signals to the Arduino Nano and Microchip SBD BT attached to the top of the footwear. We also performed two types of measurements: one in which the insole sensor was installed inside the sandal, and the other in the shoe.

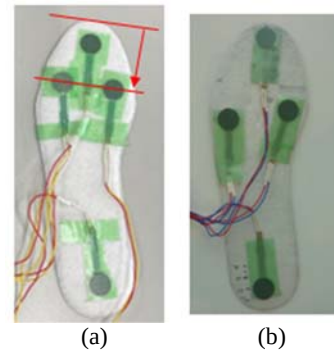


Fig. 1. Sensor position.

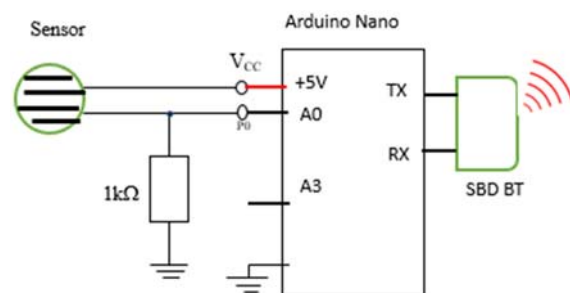


Fig. 2. Measurement system.

During the measurement, the participant walked for approximately 30 or 60 s, with and without motion restriction on the right knee joint, using a supporter, for a distance of approximately 3 m. A video was captured from the front for a separate analysis. When walking, the participant repeatedly performed U-turns and straight turns. The sensor position was varied from the tip of the insole to examine the relationship between the sensor position and the presence or absence of motion restriction in the right knee joint. At 70 mm, the sensor position was lower than that of the inside and outside sensors, as shown in Fig. 1(a).

Furthermore, measurements were taken with the sensor position corresponding to the toe, 50 mm from the tip, that was similar to that of commercially available smart insoles.

Considering that the sensor position in the heel area also significantly affected the measurement results, we conducted measurements at positions 20,

30, and 40 mm away from the heel tip. Furthermore, because sufficient mobility could not be secured depending on the measurement location, measurements were performed by walking in only one direction for up to 3 m without U-turns.

The participant was a male in his 60s. Exercise restriction was simulated using a supporter in the knee area.

3. Results

3.1. Output Waveforms from a Self-made Insole Sensor

With the sensor positioned 15 mm from the tip of the insole, the measurement results during walking with and without motion restrictions are shown in Figs. 3(a) and (b), respectively. The position of the peak differed in each cycle, and the output voltage was lower in certain cycles. In the absence of motion restriction, the signal decreased with time.

Assuming that a low-output state below 50 % of the peak value corresponded to the state at the U-turn, we compared the difference between the peak (maximum value) and the minimum values among four consecutive values in the interval up to the low-output value before the first U-turn. In this case, this interval was used as a break. The difference tended to be larger under these limitations. The values of the sensor outputs other than those of the toe sensor were calculated based on the time of the toe sensor output.

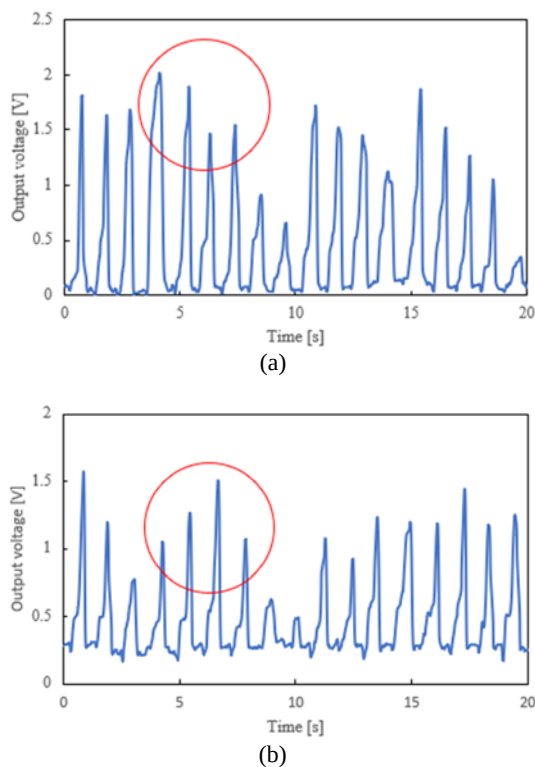


Fig. 3. Measurement results during walking without (a) and with motion restriction (b).

In measurements that did not involve a U-turn, the measurement distance was short, with a maximum 3 m; therefore, only three sensor peaks were obtained. Therefore, we decided to use the average peak value from these three points and the slope of the point where the rate of decrease was the maximum after the peak.

3.2. Comparison of Average Output Voltages and the Difference Between Maximum and Minimum Output Voltages

The sensor position from the toe was varied from 15 mm to 70 mm. Fig. 4 illustrates two characteristic examples: the average of the four sensor output voltages and the difference between maximum and minimum output voltages. In the figure, Toe represents the case without motion limitation, ToeR represents the case with right knee motion limitation, and the labels marked as dif represent the maximum-minimum voltage differences.

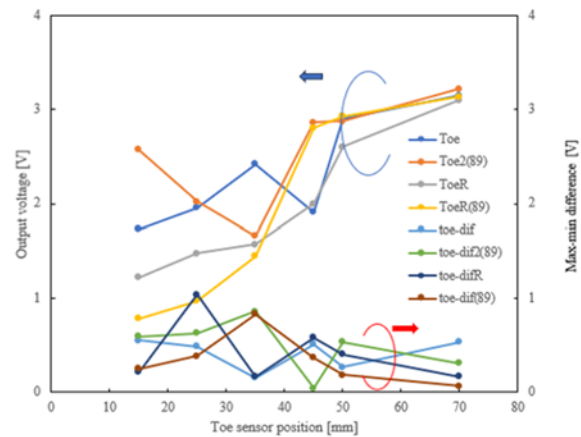


Fig.4. Average of four sensor output voltages and the difference between maximum and minimum voltages.

Different results were obtained when the sensor position of the toe was changed without motion restriction. The output was such that the characteristics shifted to the left, except for the area close to the tip; however, the output voltage at a distance closer to the tip increased. The trend of the difference between the maximum and the minimum values did not change significantly with or without motion limitation, or with different measurements. The data shown as 89 in the figure were measured with the inner and outer sensor positions set at 80 mm and 90 mm from the tip, respectively.

3.3. Change in the Peak Value by the Self-made Device

A decrease in the output voltage was observed with the passage of measurement time when the sensor

position on the toe was changed. The variation in the peak value at the sensor position on the toe is shown in Fig. 5. The horizontal axis represents the point number evaluated as the peak, not time. The unit for the number of measuring positions was based on the nature of the evaluation software. The peak points correspond to the measurement times. At 50 mm, the values were almost stable, except at the U-turn point.

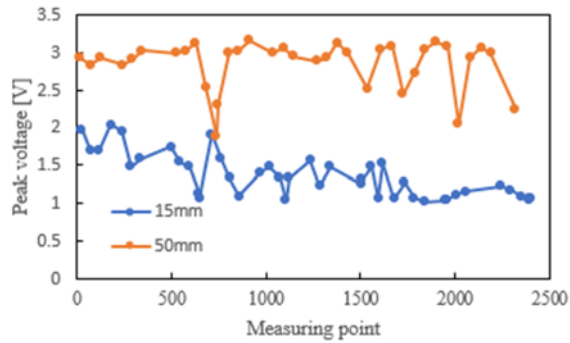


Fig. 5. Change in the peak value with no motion limitation by the self-made device.

Fig. 6 shows an example of the results obtained when the toe sensor position was set at 15 mm and the self-made insole was placed in sandals and shoes. No motion restrictions were applied to the knees during measurement. Compared with the case using sandals, when measurements were taken using shoes, the fluctuation in the width of the peak output was larger, but no decrease in the output signal was observed.

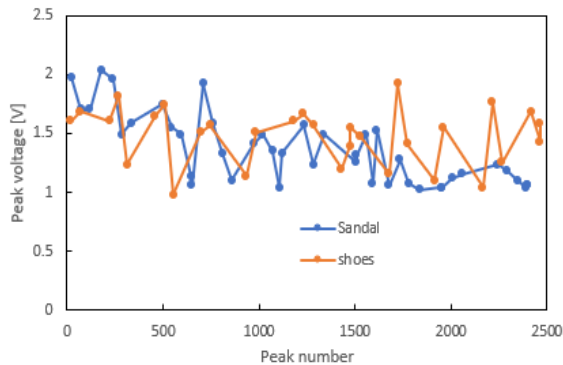


Fig. 6. Comparison of output voltages when a self-made insole was built into a sandal and shoe.

3.4. Output Voltage with Different Heel Positions

Measurements at different heel positions were performed with shoes on. Because the range that could be considered to correspond to the heel was narrow, the sensor positions were only at three points: 20, 30, and 40 mm. The difference between the maximum and the minimum outputs was small, and no influence of

the position was observed. When movement was restricted, the closer the sensor was to the end of the calcaneus, the larger was the sensor output; when movement was restricted, the sensor output was smaller. In Fig. 7, N and R represent the presence and absence of movement restrictions, respectively.

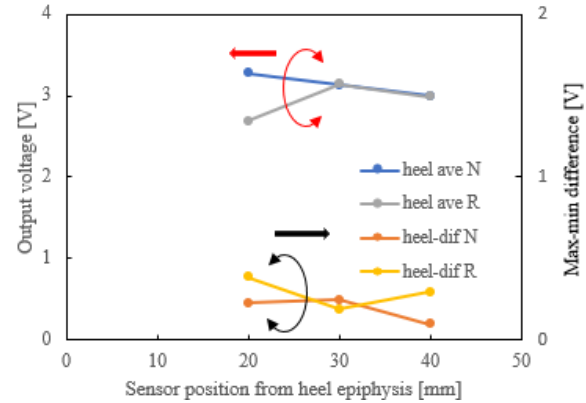


Fig. 7. Output voltage with different heel positions.

3.5. Output from Smart Insole

The output from the smart sensor was obtained for confirmation because the output from the self-made insole sensor decreased with time. The results are shown in Fig. 8. Because the sensor position of the smart insole did not change, slight variations in the amplitude were observed, whereas the period remained relatively constant. This differed from the observed output pattern of the self-made insole sensor.

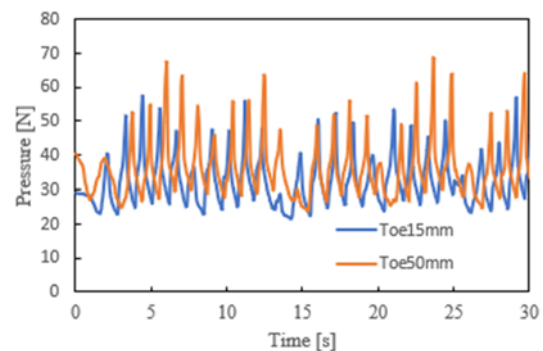


Fig. 8. Output of the smart insole sensor when the position of the self-made sensor was changed.

3.6. Classification

As reported in SEIA' 2022 and our previous paper, the set of peak values and the steepest slope values in the decreasing portion after the peak reflected the participant's characteristics. In the current study, because we did not have sufficient measured data, we did not use machine learning for analysis, but instead investigated the possibility of classifying whether a

subject had movement restrictions based on a combination of sensor outputs from four locations and the slope.

Figs. 9 and 10 show the cases where the toe sensor positions were 15 mm and 50 mm, respectively; Support Vector Machine (SVM) was used as the classification method. Figs. 11 and 12 show the cases

where a decision tree was used. The data used for this classification were analyzed using the data from shoes. The black circle indicates no movement restriction, and the red circle indicates movement restriction on the right knee. Only the toe sensor position was changed at two points, 15 mm and 50 mm, and the other sensors were set as shown in Fig. 1(b).

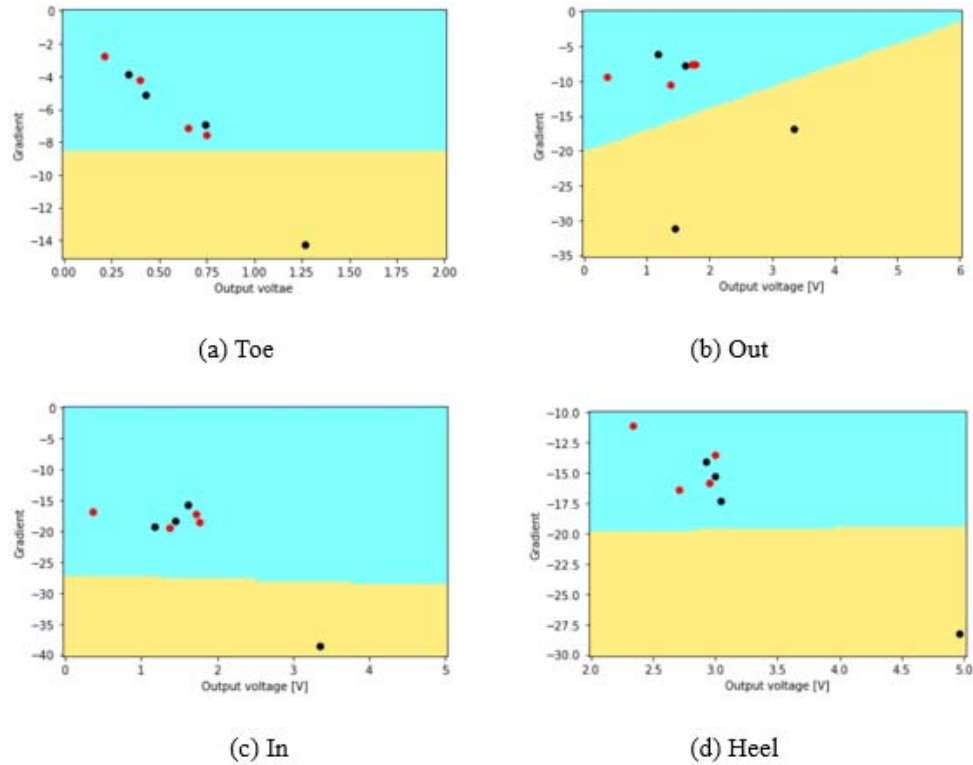


Fig. 9. Classification using the Support Vector Machine method. The toe sensor position was 15 mm.

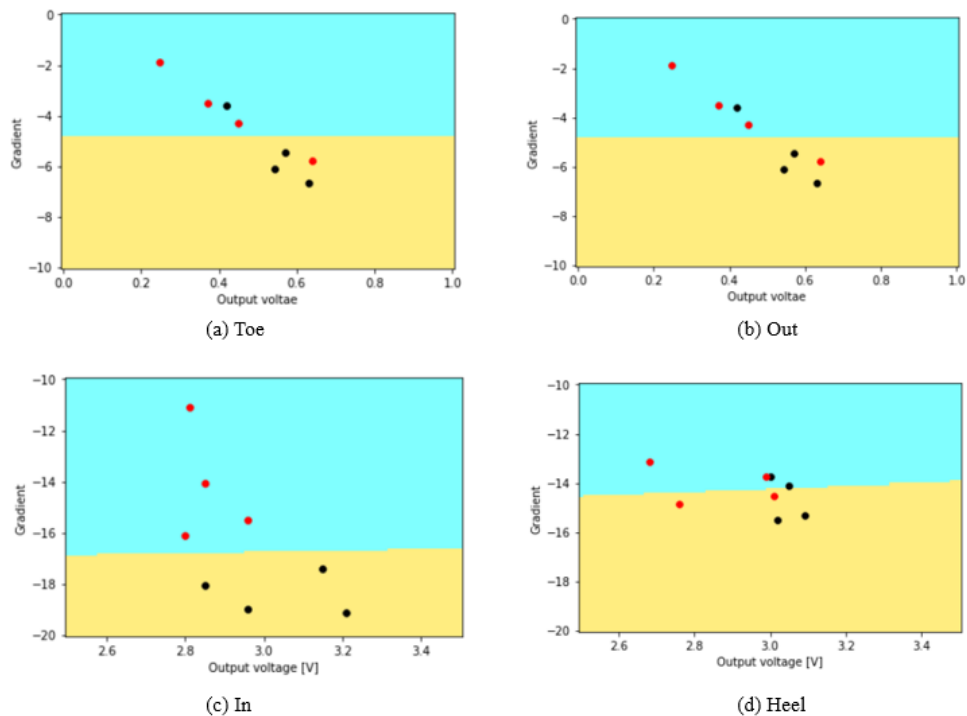


Fig. 10. Classification using the Support Vector Machine method. The toe sensor position was 50 mm.

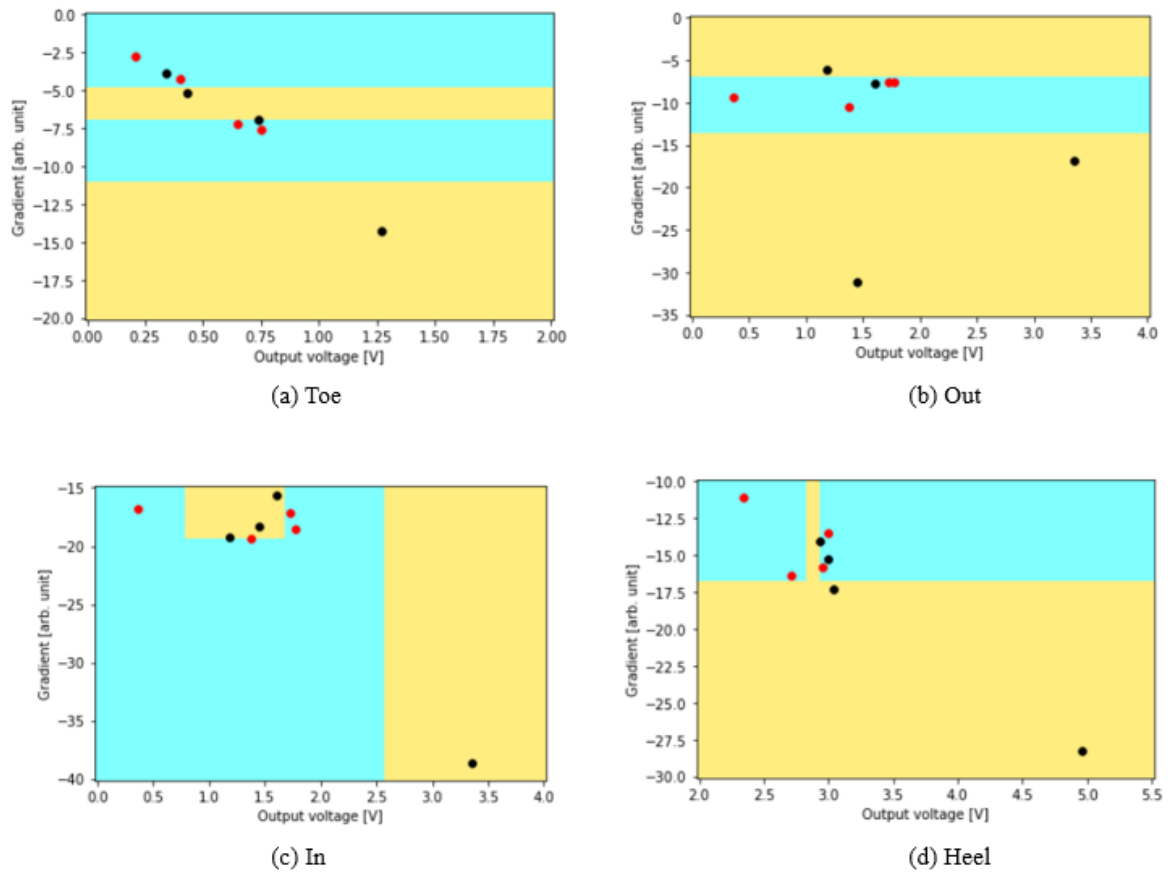


Fig. 11. Classification using the decision tree method. The toe sensor position was 15 mm.

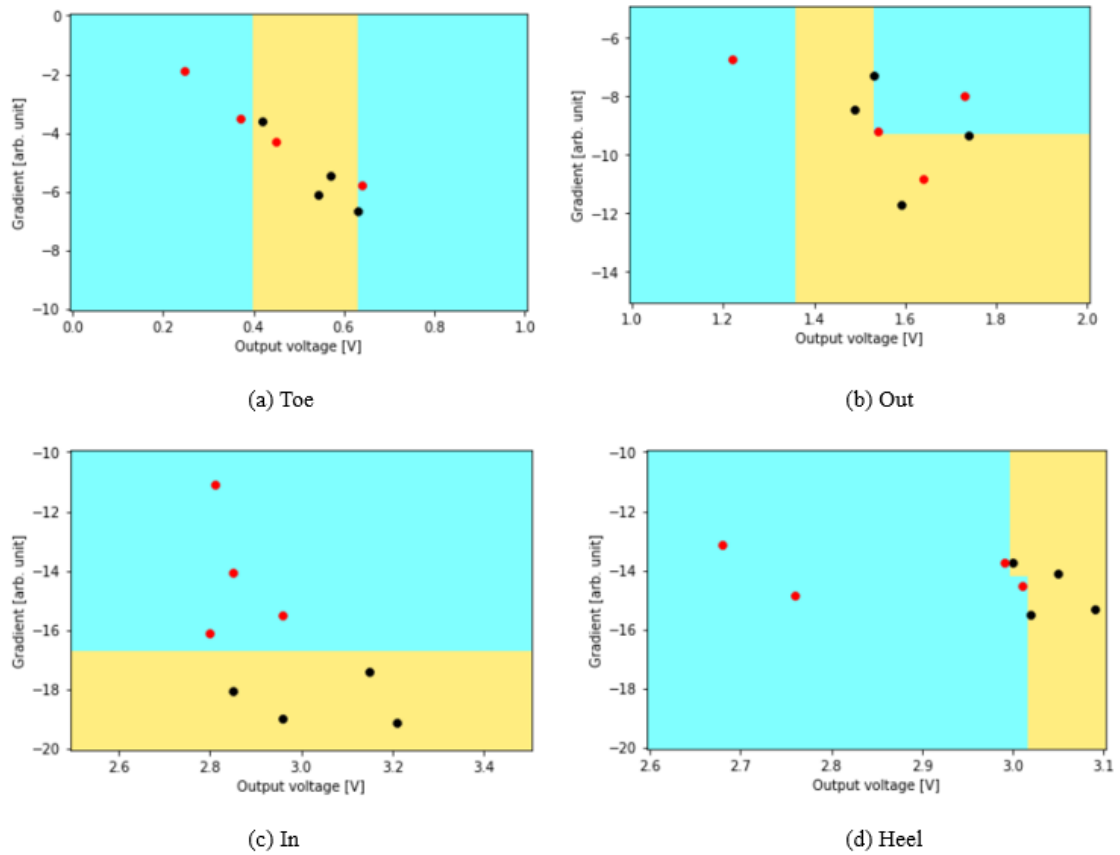


Fig. 12. Classification using the decision tree method. The toe sensor position was 50 mm.

The accuracies of the classification results are presented in Table 1. The accuracy was expressed as a percentage. In this measurement, the accuracy of classification was higher when inner data were used.

Table 1. Difference in accuracy expressed as a percentage depending on the classification method.

	SVM15	SVN50	DT15	DT50
Toe	62.5	75	87.5	87.5
Out	75	50	87.5	87.5
In	62.5	100	100	100
Heel	62.5	50	87.5	100

The classification results were further confirmed using the k-means method, an unsupervised learning method for classification. The triangles in the figure represent the centers of the clusters.

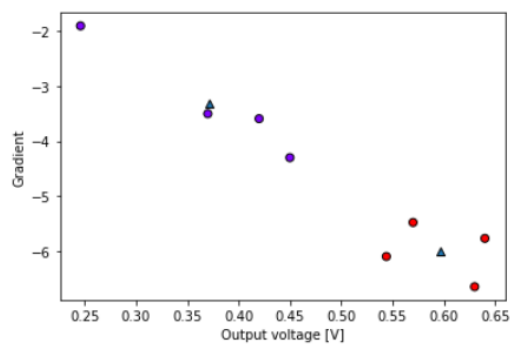


Fig. 13. Classification using the k-mean method. The inside sensor position was 15 mm.

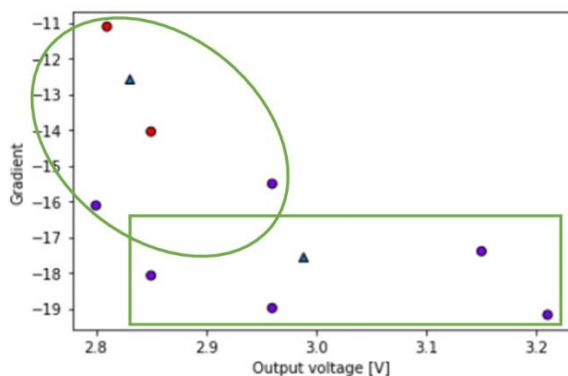


Fig. 14. Classification using the k-mean method. The inside sensor position was 50 mm.

4. Discussion

4.1. Sensor Position and Motion Limitation

Up to a sensor position of approximately 35 mm, the output voltage was larger when no restriction was applied than when a restriction was applied. This was

probably because of the smaller kick of the foot during walking when restricted, and the foot was flat with the right foot landing evenly. The toe of the participant was positioned 40 mm from the base of the toes to the tips of the feet. Therefore, the toe sensor was closer to the outside and inside sensors at a position of 45 mm or more, such that the output was almost the same, irrespective of the limitation. This supported the case in which the output data from the sensors on the toe side varied considerably depending on the sensor position around the base of the toes. In contrast, minimal changes were observed when the toes were closer to the center of the foot. In addition, the range between the maximum and the minimum values increased when a restriction was applied because the landing of the foot at each time during walking varied.

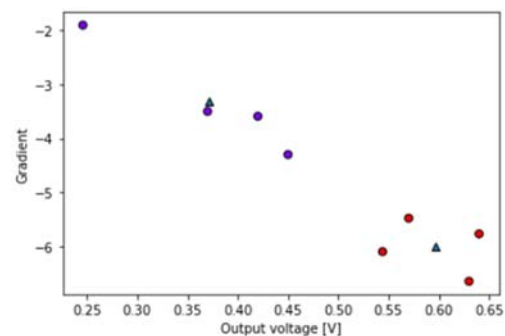


Fig. 15. Classification using the k-mean method. The heel sensor position was 50 mm.

Unlike sandals, shoes are less loose in the width direction, and the reduction is thought to be small because a commercially available insole is layered from the top. The reason for the large variation was that the shoe was loose in the length direction owing to the shape of the shoe, causing the position of the foot to shift in the length direction in the shoe when walking, and the toe area applied.

In the present example, the output voltage tended to increase closer to the heel end when no movement restrictions were applied to the sensor position at the heel. When exercise restrictions were added to the knee area, no difference was observed owing to flat feet. Therefore, the degree of ankle rotation could be detected.

4.2. Comparison of Two Types of Insole Sensors

By taking advantage of the ability to easily move the position of the sensor attached to the insole, we were able to study the differences in the output depending on the sensor position, that cannot be detected using commercially available insole sensors that have a fixed sensor position. This enabled to clarify the effect of the toe length on the sensor output. This also demonstrates the importance of the therapist

in ensuring that the sensor was fixed exactly in the desired position. Sandals were chosen for this introductory experiment. However, the reproducibility must be improved by repeating the experiment regarding the dependence of the sensor position using shoes that are thought to have less deviation in the insole position.

4.3. Consideration of Classification Methods

Although the number of experiments conducted was small, we successfully demonstrated that decision tree classification based on the set of peak values and the steepest slope value in the decreasing portion after the peak could be used to classify the data into two groups. However, the boundary areas did not significantly differ. Thus, the amount of data must be increased, and a classification method such as a support vector machine must be considered.

The results showed that using the peak voltages of the toe, medial, and heel sensor outputs and the slope of the decrease after the peak as features in the SVM and decision tree analyses might be effective. Furthermore, the results obtained using the k-means method, which is an unsupervised learning method, suggested that classification using data from the medial and heel sensors was effective. As shown in Figs. 13, 14, and 15, the classification accuracies using the inside at 15 and 50 mm and heel at 50 mm were not considered high. The most accurate case was the sensor position of 50 mm; however, the cluster group contained different motion restrictions. Thus, we must obtain experimental results to improve accuracy.

5. Conclusions

The sensor position corresponding to the participant characteristics must be considered such that the therapist can obtain the desired data using an insole sensor. However, owing to cost constraints, features that consider variations in sensor positions must be selected. We observed that the optimization parameter of the classification candidate to select the better sensor position was the slope that indicated a decrease after the peak value. This result confirmed the increase in the experimental results.

Acknowledgments

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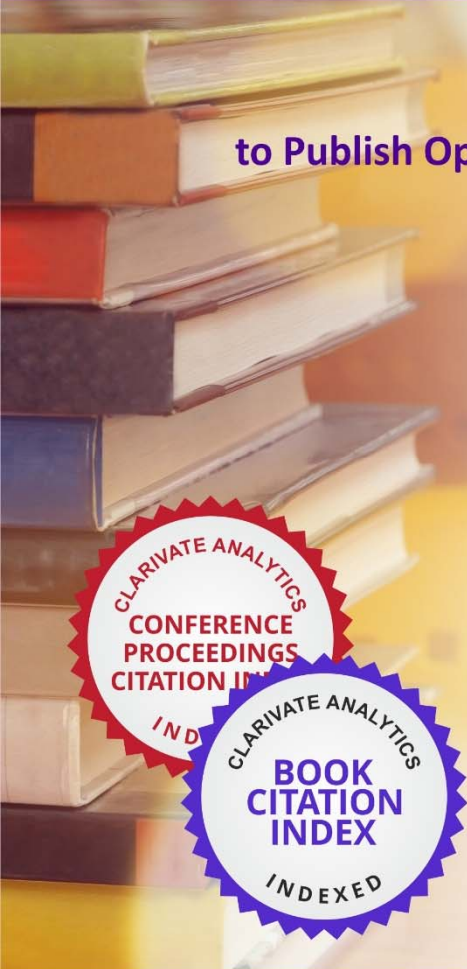
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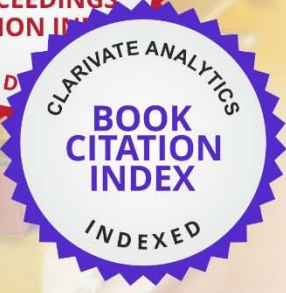


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Exploring the Assessment of Steps Using Insoles with Four-Part Pressure Sensors

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Abstract: This study focused on the potential use of smart insoles incorporating four-part pressure sensors in the field of rehabilitation. The assessment of walking not only addresses walking issues but also contributes to understanding a person's health condition because the health condition manifests in the manner a person walk. With the aim of assessing the influence of activity on the body using digital devices, we investigated walking steps before and after using a walking rehabilitation robot using a wireless smart insole with four pressure sensors on each side and an accelerometer attached to the shoe. This study explored the disparities in the arrangement of pressure sensor data integrated into the insole, differences resulting from analysis methods, and their relationship with the accelerometer were investigated. The analysis results for the walking steps before robot attachment, during robot-assisted walking, and after robot attachment of distinctive features for each of the four parts of the insole demonstrate the potential of the pressure-sensor-equipped smart insole in detecting changes in walking patterns.

Keywords: Smart insole, Accelerometer, Activity assessment, Gait change detection, Rehabilitation.

1. Introduction

The manner of walking changes before and after activities, such as exercise, meals, and bathing, depending on the physical and mental conditions. Activities contribute to relaxation and fatigue, leading to changes in physical and mental conditions. The assessment of walking not only addresses walking issues but also contributes to understanding a person's health condition, because the health condition manifests in the way one walks. Walking speed is sometimes called the "sixth vital sign" and can provide

insights into the body's state beyond just locomotion [1]. Wearable devices capable of measuring activities have rapidly gained attention in recent years and can also be used for rehabilitation for daily activities [2, 3]. The sensors used in these devices include acceleration, optical, temperature, and pressure sensors [4-7]. A large amount of data can be acquired using various sensors. However, the more abundant the collected data, the more complex and challenging it becomes to analyze the underlying implications. Furthermore, an increased number of sensors is often correlated with increased cost and device operation

complexity. Therefore, focusing on which data are valid and how they are needed is critical for determining an individual's health condition [8, 9]. The equipment and analysis must be easy to use and understand by older people, people facing health issues, and supporting medical professionals.

In recent years, the research and development of smart insoles that record digital data to assess the effects of aging and disease for purposes such as fall prevention have progressed [10-22]. Over the years, the indications of insoles for orthopedic diseases, including osteoarthritis, diabetes, and other ailments common among older people, have been investigated in the rehabilitation and health promotion fields [23-27]. Smart insoles have the potential to assess the conditions of various illnesses and detect changes in walking patterns based on an individual's health status. Extracting crucial aspects of sensor placement and analysis contributes to practicality in rehabilitation. We have investigated the possibility of assessing how activities influence the mind and body using digital devices [7, 15, 22]. To understand the changes in health and activity, we used pressure-sensor-integrated insoles, accelerometers attached to shoes, pressure-sensor-equipped floor mats and bed mats, and wristbands incorporating optical sensors and accelerometers.

In this study, we used a robot for rehabilitation to improve walking. We examined walking before and after robot application using insoles with pressure sensors and accelerometers attached to the shoes. Additionally, considering the potential for obtaining information related to acceleration without using an accelerometer, we examined the relationship between the data from the pressure sensors on the insole and the accelerometer. We analyzed the correlation between the acceleration data and the peak values, maximum rate of decrease, and foot-ground contact time derived from the insole data at each step. The insole data were calculated for the heel, toe, inside and outside parts of the insole. Furthermore, we calculated the foot-ground contact time from the heel contact to toe-off and from one heel contact to the next and studied its relationship with acceleration data.

2. Experimental Method

2.1. Devices

We used a wireless smart insole (FEELSOLE®) that had pressure sensors. It enables measurements in four parts (the toe, heel, inside, and outside) of each foot, resulting in a total of eight parts for both feet. The insoles were calibrated before use. Calibration was performed four times: with no pressure and no feet in shoes, standing on both feet, and standing on one foot on each side. The sampling frequency was set at 50 Hz. Data were stored on the cloud using ORPHE ANALYTICS and downloaded in a CSV format.

An ORPHE CORE® accelerometer was used in this study. The data were uploaded to the cloud using the ORPHE ANALYTICS application, and the upload was confirmed by downloading the data in a CSV format. The sampling frequency was set at 200 Hz. We used two triaxial accelerometers, one for each leg, resulting a total of two devices. The assessments were conducted by attaching the devices to the outer side of each shoe, with one device on each foot. Data from both smart insoles and accelerometers were synchronized using ORPHE ANALYTICS. The robot used in this study was the Orthobot®, which is used for walking and gait rehabilitation. When attached to a long-leg brace, the robot steers its lower limbs in favorable movement patterns. The placement of the sensors is depicted in Fig. 1, and a photograph of the robot equipped for walking is shown in Fig. 2.



Fig. 1. Insole sensors and accelerometers.



Fig. 2. Walking with robot.

2.2. Measurements

We measured preusage walking, walking while wearing the robot, and postusage walking using smart insoles with built-in pressure sensors and shoes fitted with accelerometer sensors. The subject performed three walking trials of approximately 20 seconds each while wearing the walking assistance robot. The data from the third trial were analyzed. Gait analysis after use was conducted twice: once at 5 minutes and the other at 12 minutes after robot use. The 1000th-6000th data points were analyzed, excluding the periods immediately after the start and shortly before the end of the experiment. The subject was a man in his 60s without walking impairment who wore the robot on his right leg. This study was approved by the Human Research Ethics Committee of Teikyo University of Science.

2.3. Peak Detection

Peak values were identified from the insole data, representing the points of the highest sensor force application for the four parts (heel, toe, inside, and outside of the insole) during a single foot-ground contact. The peak values were detected using the `find_peaks` function from the Python library, SciPy. The threshold for peak determination was set at 50 % of the maximum value for each trial for the heel, toe, inside, and outside parts of the insole. Multiple peak values were calculated for each gait. In addition, the mean peak value and the maximum value from one heel contact to the next heel contact, that is, the maximum peak value between each step, were computed.

2.4. Determination of Decrease Rate

The rate of decrease indicates a decline in the value following the peak. In this study, it was calculated by determining the difference in the weighted averages of adjacent data points. In other words, the difference between the weighted averages of the x and $x+1$ data points were computed. The weighted average was obtained using five values (the target value and two values each before and after) and calculated as follows. Because of the significant influence of the central region, the percentages were calculated by assigning 40 % to the target value of the waveform, 20 % to the values before and after one target, and 10 % to the values before and after two targets. The weighted average difference can have positive or negative values; however, only negative values were used in the calculations. We calculated the mean absolute values of the negative numbers and determined the minimum value for each step.

2.5. Determination of Acceleration

Accelerometer data were examined by calculating the absolute value in each case and obtaining the square root of the sum of squares of the values along the X-, Y-, and Z-axes. The term "acceleration data" in the following refers to the square root of the sum of the squares of accelerations along three axes. The mean value for each walk and the maximum, minimum, and standard deviations of the acceleration at each step on the left and right sides were obtained.

2.6. Foot Contact Time for Each Insole Part

We calculated the ground reaction time of each sensor for the eight parts on both sides, which was the time taken for each of the eight parts to move from ground contact to lift-off. Additionally, we calculated the time from the heel contact to toe lift-off, the time from one heel contact to the next heel contact, and the time for each step, known as the step duration.

The minimum and peak values during a single walking cycle were used to calculate the ground contact time. The calculation method was as follows. The minimum value for each of the eight parts, including the left, right, heel, toe, inside, and outside, was determined. A minimum value indicates the least responsive sensor. For the peak values, we calculated the peak value at multiple ground contact times during each walking trial for the left, right, heel, toe, inside, and outside and determined the mean of the multiple peak values. To determine the ground contact and lift-off times, we added 0.2 times the difference between the mean of the peak values and the minimum value to the minimum value, setting it as the threshold.

$$thresh = Min + (Peak - Min) \times 0.2 \quad (1)$$

The initial time within the period at which values above this threshold persisted was designated as the start time, and the final time was designated as the lift-off time. The difference between the lift-off time and ground contact time was considered the ground contact time. Specifically, for each foot (left and right), we determined the first and last times above the threshold within the data between the heel start time and subsequent heel start time for each of the four parts. The values for the left heel, toe, inside, and outside were those between the start of the left heel and that of the subsequent heel. Similarly, for the right foot, the values were calculated between the right heel start time and subsequent start time. The heel start time was considered to correspond to the heel strike.

2.7. Foot Contact and Acceleration Analysis

The maximum peak value, maximum rate of decrease, foot-ground contact time, and maximum acceleration during the duration from the left and right heel contacts to the subsequent heel contacts were extracted and compared via correlations. The insole data, including the maximum peak values and the maximum rates of decrease, were collected for four parts: the heel, toe, inside, and outside of the insole. Data were separately collected for the left and right devices and for the left- and right-foot-ground contacts, resulting in four distinct patterns. The foot-ground contact duration was measured for four parts, and the measurements were conducted from the heel contact to toe-off separately for the left and right sides. The maximum acceleration was measured in four distinct patterns: left and right devices, and left and right foot-ground contacts.

For each step, the maximum peak value, maximum rate of decrease, foot-ground contact time, and maximum acceleration were calculated. Data for steps were obtained for four trials: before robot attachment, during attachment, 5 minutes after attachment, and 12 minutes after attachment. A comparison between the left and right feet was conducted for the right-foot-ground contact after the left foot made contact, and the right-foot-ground contact immediately before the left

foot made contact. In other words, the comparison focused on the right-foot-ground contact in two steps: one occurring after the ground contact of the left foot, and the other shortly before the ground contact of the left foot. We examined the relationship by investigating the correlations between the maximum acceleration, maximum peak value, maximum decrease rate, and the duration of foot-ground contact and calculated Pearson's correlation coefficient. Pairs with high correlation were extracted, and an analysis was conducted on whether the data from the insole and the data from the accelerometer were from the same-side foot or the opposite-side foot. Furthermore, we made a distinction between data from the same step durations and data from opposite step durations (for example, acceleration during the right step and insole during the left step; see Fig. 3). The analysis also included an examination of the location of the insole.

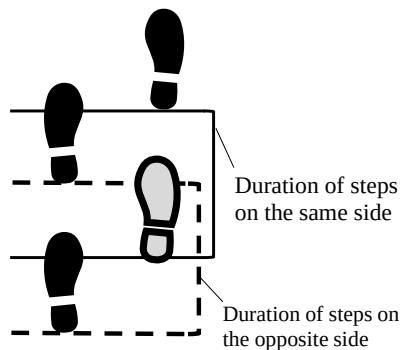


Fig. 3. Two periods in three steps.

3. Results

3.1. Peak Values of Insoles

The mean peak values for 5 and 12 minutes after robot usage were compared with the values before robot usage. The value before robot usage was considered 1, and the rates of change were calculated. The values are listed in Table 1.

Table 1. Rate of change in peak values.

Part	Before	During	5 min after	12 min after
L_heel	1.00	1.12	1.01	1.04
L_toe	1.00	0.97	1.03	1.03
L_inside	1.00	1.11	1.13	1.09
L_outside	1.00	0.84	0.86	0.96
R_heel	1.00	0.91	1.05	1.20
R_toe	1.00	0.44	0.96	0.93
R_inside	1.00	0.93	1.09	1.12
R_outside	1.00	0.48	0.90	0.83

In terms of the peak values, the values decreased in some areas, but overall, the peak values increased.

From the data for 12 minutes after robot detachment, on the side where the robot was attached, the right side showed a decrease on the outside and an increase on the inside. The toe part showed a decrease, whereas the heel part showed an increase. During robot attachment, the attached side showed a decrease. The peaks decreased, indicating a decrease in momentum.

3.2. Rate of Decrease

The difference in the weighted mean difference, that is, the difference in the rate of decrease, at each walking session was calculated using the pre-robot as the reference. The mean values for each walk were compared (see Table 2).

Table 2. Rate of change in decrease.

Part	Before	During	5 min after	12 min after
L_heel	1.00	1.09	1.05	1.04
L_toe	1.00	1.03	1.39	1.50
L_inside	1.00	1.33	1.60	1.53
L_outside	1.00	0.74	0.98	1.38
R_heel	1.00	1.14	1.19	1.56
R_toe	1.00	0.34	0.94	0.96
R_inside	1.00	0.84	1.18	1.30
R_outside	1.00	0.45	0.79	0.79

In terms of the weighted mean difference, that is, the decrease rate, the values decreased in some areas, but overall, the values increased. Based on the data for 12 minutes after robot detachment, on the side where the robot was attached, the right side showed a decrease on the outside and an increase on the inside. The toe part showed a slight decrease, whereas the heel part showed an increase. During robot attachment, the attached side showed a decrease. The changes were minimal, indicating a slow and gradual transformation.

3.3. Acceleration

For acceleration, in addition to the mean value, we calculated the minimum value, maximum value, and standard deviation to assess the magnitude of the movement variability. Table 3 lists the ratios during and after robot usage, with the pre-robot condition as the baseline for each statistical parameter.

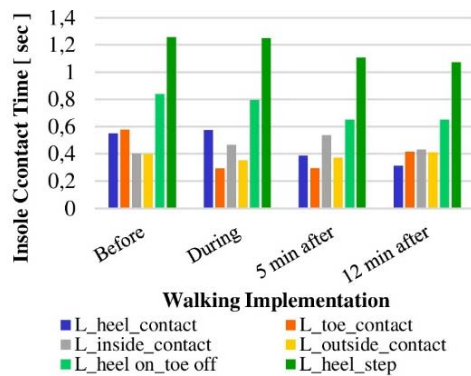
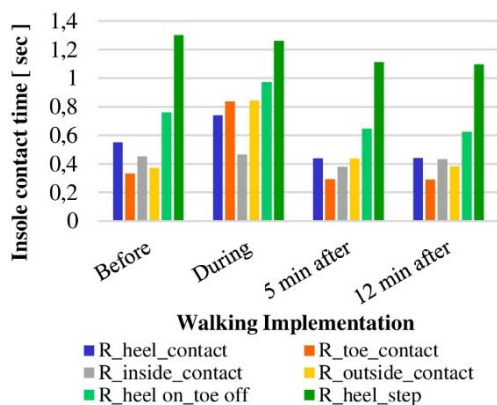
The minimum values of acceleration on the left and right sides decreased, but the other values increased for the measurements conducted 5 minutes after detachment. The left maximum value at 12 minutes slightly decreased. The standard deviation increased by more than 40 % on both the left and right sides at 5 and 12 minutes after detachment. During the robot attachment, the right-side maximum and left-side minimum values increased, whereas the others decreased.

Table 3. Rate of change in acceleration.

Part	Before	During	5 min after	12 min after
L_mean	1.00	0.96	1.12	1.08
R_mean	1.00	0.89	1.13	1.10
L_max	1.00	0.85	1.28	0.96
R_max	1.00	1.45	1.75	1.10
L_min	1.00	1.63	0.95	0.83
R_min	1.00	0.80	0.72	0.44
L_std	1.00	0.97	1.45	1.43
R_std	1.00	0.83	1.53	1.41

3.4. Foot Contact Time for Each Part

In addition to the four regions of the insole, we calculated the time from the heel to the toe and from one heel to the next heel, representing the time for one step. The results for the left and right insoles are presented in Fig. 4 and 5, respectively. The unit is in seconds. The figure illustrates the mean values for six items in each walking condition: before robot attachment, during attachment, 5 minutes following detachment, and 12 minutes following detachment. The bars in the figure are blue for the heel, red for the toe, gray for the inside, yellow for the outside, bright green for heel to the toe and dark green for one step.

**Fig. 4.** Left-foot-ground contact time.**Fig. 5.** Right-foot-ground contact time.

During the robot use, the time spent on the left toe decreased, whereas the time spent on the right toe increased. After the robot was used, an overall tendency of decrease in time was observed. Table 4 lists the percentage changes relative to the pre-robot conditions.

While walking with the robot attachment, the right foot, which was attached to the robot, experienced increased durations of heel, toe, inside, outside, and heel ground contact to toe release.

Table 4. Rate of change in foot contact time.

Part	Before	During	5 min after	12 min after
L_heel	1.00	1.05	0.71	0.57
L_toe	1.00	0.51	0.51	0.72
L_inside	1.00	1.16	1.33	1.08
L_outside	1.00	0.88	0.94	1.03
L_heel on -toe off	1.00	0.95	0.77	0.77
L_heel_step	1.00	0.99	0.88	0.85
R_heel	1.00	1.35	0.80	0.80
R_toe	1.00	2.52	0.88	0.88
R_inside	1.00	1.03	0.84	0.96
R_outside	1.00	2.27	1.18	1.03
R_heel on -toe off	1.00	1.28	0.85	0.82
R_heel_step	1.00	0.97	0.86	0.84

Within the plantar ground contact time of the left foot without the robot, the left foot without the robot was more than 20 % shorter at the toe and less than 20 % shorter at the heel contact to toe-off and heel contact to next heel contact. In contrast, the heel and inside were longer. For both the left and right sides, the time from heel contact to the next contact decreased. The duration of the left-heel contact without the robot increased, and the duration of the toe contact decreased. In addition, the duration for the outside of the insole decreased, whereas that for the inside increased. While walking with the robot attachment, the length of time spent by the left leg, which was not attached to the robot, shifted from the toe to the heel and from outside to inside.

Five minutes after the robot was removed, the pace of walk became significantly fast, with durations more than 20 % shorter on the left heel, toes, and from the heel ground to toe-off, and 10 % shorter overall on the other parts. The two parts that were longer were the left inside and the right outside. On the left side without the robot, an increase in the loading time shifting from the outside to the inside was observed. whereas, with the robot attached to the right, an increase was observed for the loading time shifting from the inside to the outside.

Even after 12 minutes of robot-assisted walking, a trend similar to that after 5 minutes was observed. In comparison before the robot was attached, the difference in the trend after 5 and 12 minutes was that the left outer sides were longer than before the robot

attachment. Compared to the case before robot attachment, the changes only after 5 and 12 minutes showed that on the left side, the inside was shorter, and the outside was longer, and on the right side, the inside was longer, and the right outside was shorter.

An exceptional ground reaction, presumed to be associated with U-turns and different from typical steps, was observed. Five minutes after the robot was removed, a step was observed in which two inside peaks appeared between the left heel peak and the subsequent peak. The raw data from the sensors are shown in Fig. 6. The calculation of foot-ground contact time was based on the left heel contact; therefore, in this step, the extracted foot-ground contact times for both the inside and outside increased. A graph of the foot-ground contact times was plotted (Fig. 7). Despite being an exceptional step, it has not been excluded and is included in the calculations of the foot-ground contact time.

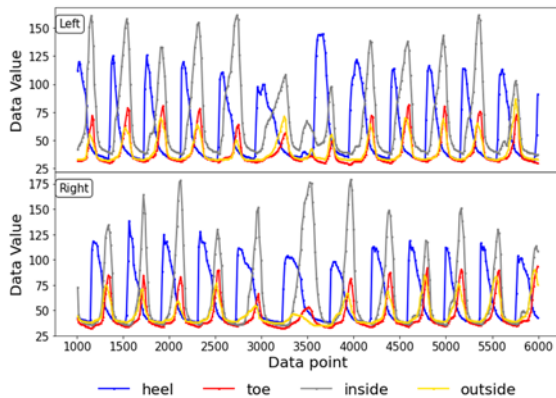


Fig. 6. Raw data for 5 min after robot detachment.

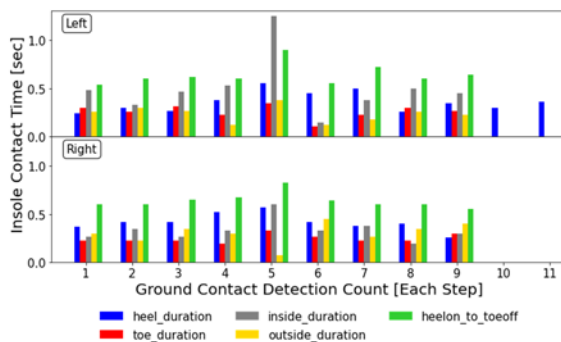


Fig. 7. Foot-ground contact time per step 5 min after robot detachment.

While U-turns were performed in each walking session, such exceptional steps were observed only walking when 5 minutes after removing the robot. In calculating the foot-ground contact time, a step in which only the heel was extracted was also observed in other trials. The calculation method for extracting foot-ground contact time used in this study is considered to be more suitable for utilizing heel data compared to the other three parts.

3.5. Foot-ground Contact and Acceleration

The number of steps in each walking trial, combined for the left and right sides, was 17 before robot attachment, 17 during attachment, 20 at 5 minutes after removal, and 20 at 12 minutes after removal. A total of 74 steps were taken. We examined the relationship by investigating the correlations between the maximum acceleration, maximum peak value, maximum decrease rate, and the duration of foot-ground contact. Pearson's correlation coefficient was used for the calculations.

The results of the correlation analysis revealed no items with a correlation coefficient of 0.6 or higher. Items with a coefficient of 0.4 or higher included 25 pairs in the relationship between the right step with the attached robot and the preceding left step in terms of time. There are 24 pairs in the relationship between the right step with the attached robot and the subsequent left step. Of the 49 pairs with relatively high correlation, 17 were pairs in which the accelerometer and insole were on the same side of the foot, and 32 were pairs in which they were on opposite sides (Table 5). The correlation tended to increase when the accelerometer and insole were placed on different sides of the foot. In addition, we checked the time period from which 32 pairs were extracted in which the acceleration and insole were on opposite sides and found 14 data pairs for the same time period and 18 data pairs for different time periods, that is, at different left and right step times. Through a detailed study of the acceleration at different time periods for 18 pairs, the acceleration data pairs during the step time of the same foot on the side for which the data were acquired were 12, and the acceleration data pairs during the step time of the other foot for which the data were not acquired were 6.

Table 5. Acceleration-Insole high correlation.

Acceleration Insole	Highly Correlated Numbers	Same Time Period	Different Time Period
Same side	17	8	9
Opposite	32	14	18

Among the 12 pairs with a high correlation between the acceleration and insole during the step period, the insole data comprised five from the toe, four from the outside, two from the inside, and one from the heel. This suggests that the insoles with a high correlation with acceleration are on the opposite side of the foot where the accelerometer is attached and are not in the same step period. Moreover, the areas of the insole with a correlation to acceleration are inclined towards the toe and slightly to the outside.

4. Discussion

The smart insole detected variations in the peak values, rates of decrease, and durations of foot-ground

contact before and after robot use. Among the four parts, the right outside, where the robot was worn, exhibited a tendency to present different results compared to the other three. In addition, changes were observed on the inside right, which might be correlated with the outside.

Five minutes after detaching the robot, based on the foot-sole ground contact time on the left side without the robot, the load time increased as it moved from the outside to the inside. However, on the right side with the robot, the load time increased as it moved from the inside to the outside. From the peak values and decrease rates after detaching the robot, the right outside showed a decrease, whereas the inside showed an increase. This suggests a potential change in the distribution of weight-bearing along the left-right axis. The following considerations are possible. On the inside of the right side, a possibility of rapid and forceful ground contact was observed during rapid movements, potentially increasing the peak values and decrease rates. Whereas, the outside experienced a decreased load, resulting in a reduction in the peak values and decrease rates, leading to a gradual change. Regarding the acceleration on the left side, all values on the left side increased based on the decrease-rate data, suggesting that the movements were accelerating.

Based on the foot-ground contact time, it was observed that the time for one step was shortened on both the left and right sides. Although a slight increase occurred on the right outside and left inside, the overall trend indicated a reduction. Upon reviewing the steps during U-turns through video observations, a walking pattern was identified in which 5 minutes after robot detachment, rotation occurred around the right foot as an axis. Analyzing the steps that deviate from the norm separately from regular steps simplifies the observation of the characteristics during normal steps. However, distinctive features may also appear during exceptional steps. It is crucial to focus on analyzing exceptional steps while concurrently examining regular steps and recognizing the significance of both aspects. In addition, the extraction of step times was most reliably detected when focusing on the heel.

In terms of the acceleration and time, it is apparent from the foot-ground contact time that the duration of a single step on the left and right sides decreased. From the acceleration data, it was observed that the acceleration decreased during landing; however, after takeoff, an overall increase in acceleration was observed, and the minimum values decreased. Considering the increased standard deviation and shift towards increased maximum values and decreased minimum values, it is possible that the movements became more dynamic. No consistent correlation was observed with acceleration. However, it is possible that data from the pressure sensor insole on the opposite side of the evaluated foot were related. In addition, a focus on the toes is suggested. The toe is a region with weaker data output and a lower load compared with other parts. It is believed that detecting

changes in walking patterns can be facilitated by implementing sensitive sensors, finely tuning their positions, and employing sensor innovations in this less-loaded region.

5. Conclusions

Distinct characteristics were observed in the heel, toe, and inside and outside regions of the insole. Incorporating sensors into insoles based on captured features for consideration of sensitivity and position is important for walking assessment. In the future, we plan to expand the dataset and investigate analysis methods to further analyze the relationship between acceleration and pressure sensors.

Acknowledgement

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Setting Point and Operation Range of a BiCMOS On-Chip BiCMOS Thermometer

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Abstract: Thermometer circuit can be designed in BiCMOS technology to measure directly the on-chip temperature right close to other functions of an Application Specific Integrated Circuit (ASIC). This paper discusses on-chip thermometry with high temperature sensitivity. The setting of an operating point around 50 °C with no-offset is discussed allowing a multiplication of the output current times ten for a better sensitivity. An analytical model based on a proportional to temperature cell and a complementary to absolute temperature cell is discussed. Linear response in the [-150 °C: +150 °C] is illustrated. However, out from this range, deviations between analytical models and simulations based on foundry models are discussed pointing the importance of the setting point depending on the temperature range.

Keywords: On-chip thermometer, BiCMOS, ASIC, CTAT, PTAT.

1. Introduction

Temperature management in electronic devices is highly recommended in the design and development of technology. Each device has its specific temperature range, and operating outside this range may lead to performance degradation (e.g., the battery's effectiveness may change due to cooling or heating [1]), or sometimes increase the rate of failure. Temperature measurement is also crucial in meeting the high reliability requirements of electric systems because elevated temperatures can cause aging [2], decreasing the lifespan of these devices [3]. In the context of space missions, managing temperature variations is sometimes required to ensure the lifetime of the mission. Moreover, controlling the device's temperature within the operational range can prevent thermal runaway of certain devices, thereby enhancing mission safety. To align with the rapid pace of technological advancement, integrated circuits are

increasingly incorporating a greater number of transistors, reaching figures greater than one hundred thousand, a scale commonly referred to as Very Large Scale Design (VLSI) [4]. Decreasing the transistor size increases parasitic resistance and transistor density, leading to an increase of Joule dissipation [5] (self-heating) caused by the flow of current passing through the conductors (i.e.: interconnection [6]). Whether improving dissipation systems, optimizing the layout or selecting low resistance conducting materials could help, it is still important to monitor and control the temperature of the chips.

This paper represents an extended version of the work presented in [7], focusing on the design of an application-specific integrated circuit (ASIC) incorporating a thermometer using IHP 130 nm BiCMOS SiGe technology and discussing the operating range/ setting point. We delve into the topology considerations for sizing this novel thermometer by expressing the analytical model and

simulate it with Cadence software, showing a simulated linear sensitivity of approximately $10 \mu\text{A}/^\circ\text{C}$ within a 300°C temperature range centered around room temperature (higher sensitivity is achievable in a smaller temperature range or with a higher voltage supply). The output signal propagates differentially, allowing for readout in current or voltage in a load without common-mode coupling. This off-chip differential signal propagation preserves the remaining functions of the ASIC (which are not discussed here) from common-mode noise contamination.

2. Design Methodology

The methodology for developing a thermometer using electronic devices commonly relies on reading the temperature coefficient of resistances (thermistors [8], RTDs, etc.) or it is based on the threshold voltage of diodes or transistors.

The temperature sensitivity is typically constrained by the direct temperature dependance of resistances or threshold voltages. This paper explores the use of two opposing semiconductor temperature-sensitive thresholds to cancel out the signal within the desired temperature range. This approach facilitates DC amplification, leading to a substantial enhancement in temperature sensitivity.

In more detail, the concept is rooted in two opposing temperature-dependent parameters inherent in a semiconductor junction: thermal voltage $V_T(T)$ and saturation current $I_S(T)$. On one hand, the thermal voltage $V_T(T)$ is proportional to absolute temperature; on the other hand, the saturation current increases exponentially with absolute temperature. Incorporating these two parameters, we introduce the junction voltage $V_J(T)$:

$$V_J(T) = V_T \ln \left[\frac{I_J}{I_S} + 1 \right], \quad (1)$$

which is a function of thermal voltage $V_T(T)$ and the ratio between junction current and saturation current $I_J/I_S(T)$, which decreases with temperature.

In equation (1), $V_T(T)$ is defined as $k_B T/q$, where k_B represents the Boltzmann constant, T denotes the temperature in Kelvin, and q is the absolute value of the electric charge of electrons. Despite the linear increase of $V_T(T)$ with T , the thermal dependencies are predominantly influenced by the saturation current I_S . Notably, I_S exhibits an exponential growth with T , resulting in a decline of $V_J(T)$, as depicted in Fig. 1.

The natural logarithm in equation (1) transforms $V_J(T)$ into a parameter that linearly decreases with T , at least in a first approximation.

In addition to the direct use of these thermal dependencies, this paper discusses how to subtract DC/offset and combine (in absolute value) two thermal dependencies, to increase the sensitivity. The thermal dependencies can be efficiently amplified and

the offset is canceled around a chosen operating temperature.

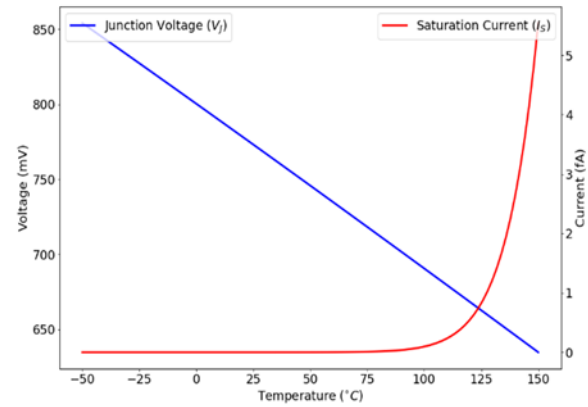


Fig. 1. The junction voltage $V_J(T)$ (in blue) decreases with temperature even though the contribution of thermal voltage $V_T(T)$ in the equation (1), owing to the exponential increase of the saturation current (in red).

3. Thermometer Circuit Design and Analysis

The idea of bandgap reference [9] is widely used in electronics. It provides a stable voltage with negligible variation in a large range of temperature by summing up signals with two opposite temperature dependencies. The voltage summation circuit adds together a complementary to absolute temperature (CTAT), and a proportional to absolute temperature (PTAT) voltage sources.

In this design, we propose a “subtraction” instead of “summation” to double the temperature sensitivity of the signal instead of canceling it. In addition, we use current sources instead of voltage sources.

The thermometer circuit consists of three components: a CTAT current source shown in Fig. 2, a PTAT current source illustrated in Fig. 3, and a crossing bridge for current subtraction. In ASICs design, where transistors are predominantly used instead of single junctions, we opt for the collector current I_C instead of the junction current I_J and the base-emitter voltage V_{BE} instead of the junction voltage V_J , employing an NPN bipolar transistor instead of a diode. In this section we will explain the working principles of the CTAT and PTAT current sources, using these fundamental parameters.

3.1. CTAT Current Source

The CTAT current source is based on the base-emitter voltage (V_{BE}) temperature sensitivity. Its schematic circuit is shown in Fig. 2. The two transistors B_7 and B_8 are mounted as a Darlington transistor [10], allowing to double the temperature

dependence. Indeed, the base-emitter voltage can be expressed and simplified as¹:

$$V_{BE} \approx 2V_T(\ln \frac{I_C/\beta}{I_S} + \ln \frac{I_C}{I_S}) \approx 2V_T \ln \frac{I_C}{I_S}, \quad (2)$$

where β is the ratio of collector and base current of the NPN bipolar transistors.

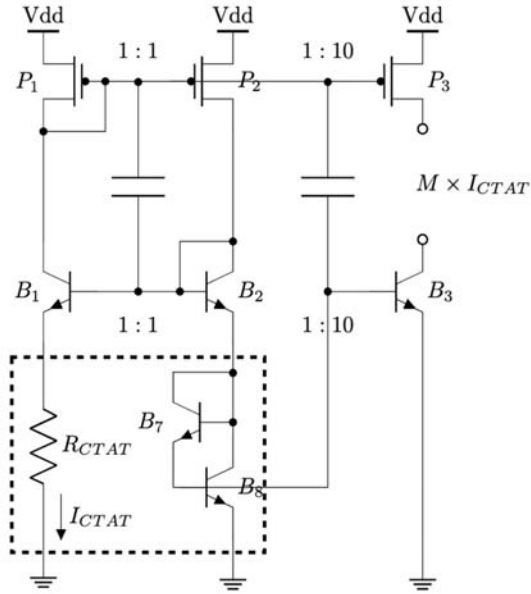


Fig. 2. CTAT current source applying the Darlington structure by combining transistors B_7 and B_8 , where the resistor R_{CTAT} plays the role of converting base emitter voltage V_{BE} into the current through current mirror $B_1:B_2$. On the other hand, the PMOS P_3 and transistor B_3 amplify the current by the factor of 10.

The voltage across the resistor R_{CTAT} is equivalent to the base-emitter Darlington voltage, as referenced in equation (2). The overall expression for the current flowing through R_{CTAT} can be determined using equation (3):

$$I_{CTAT} = \frac{2V_{BE}}{R_{CTAT}} \approx \frac{2k_B T}{qR_{CTAT}} \ln \frac{I_C}{I_S} \quad (3)$$

The saturation current I_S in equation (3) can be calculated as [11]:

$$I_S = \frac{q A_E D_n n_i^2}{W_B N_A}, \quad (4)$$

where A_E denotes the junction area, D_n is the diffusion coefficient of electrons and n_i is the intrinsic number of carriers. Otherwise W_B is the junction thickness², and N_A is the doping density.

To assess the thermal sensitivity of I_S , the temperature dependencies of parameters, D_n and n_i , are examined. D_n can be computed as:

$$D_n = V_T \mu_n = \frac{k_B T}{q} \mu_n = \frac{k_B T}{q} C T^a, \quad (5)$$

with $\mu_n = C T^a$ the electron mobility considering the case where lattice scattering is dominant [11]. The electron mobility is significant when lattice scattering dominates, a condition applicable for non-cryogenic temperature operations. The constants C and a are inherent to the material and the manufacturing process [12]. The carrier concentration n_i can be calculated with the following equation [13]:

$$n_i = \sqrt{N_c N_v} T^{3/2} e^{\frac{-E_g}{2k_B T}}, \quad (6)$$

By substituting equations (5) and (6) into equation (4), we obtain the expression for the saturation current:

$$I_S = A T^{4+a} e^{\frac{-E_g}{k_B T}}, \quad (7)$$

where $A = \frac{k_B C A_E N_c N_v}{W_B N_A}$ is a coefficient independent of temperature. By substituting equation (7) into equation (3), we ultimately derive the expression for the CTAT current:

$$\begin{aligned} I_{CTAT} &\approx \frac{2k_B T}{qR_{CTAT}} \ln \left[\frac{I_C}{I_S} \right] = \\ &= \frac{2k_B T}{qR_{CTAT}} \ln \left[\frac{I_C}{A T^{4+a} e^{\frac{-E_g}{k_B T}}} \right] = \\ &= \frac{2}{qR_{CTAT}} \left[E_g + k_B T \ln \frac{I_C}{A} - (4+a)k_B T \ln T \right] \end{aligned} \quad (8)$$

We can explore the temperature dependence of I_{CTAT} by taking its derivative, obtaining:

$$\frac{\partial}{\partial T} (I_{CTAT}) = \frac{k_B}{qR_{CTAT}} \left[\ln \frac{I_C}{A} - (4+a)(1 + \ln T) \right],$$

where a is an empirical parameter, ranging from -2 to -4 [15], so that $(4-a) > 0$ and $-(4+a)(1 + \ln T) < 0$. On the other hand, the term $\ln \frac{I_C}{A}$ can be simply estimated referring to equation (7) in the case of silicon at 300K.

It turns out that $I_C \ll A$, so that $\ln \frac{I_C}{A} < 0$. From these two approximations, we can conclude that $\frac{\partial I_{CTAT}}{\partial T} < 0$. This relationship illustrates the inverse correlation of CTAT current with absolute temperature.

¹ +1 doesn't appear in the junction equation for the remainder of the paper. This is because I_C/I_J is significantly greater than 1.

² Base width in the case of employing a bipolar transistor as opposed to a standard diode.

3.2. PTAT Current Source

The proportional to absolute temperature (PTAT) current source relies on the temperature sensitivity of a junction's thermal voltage (V_T). Illustrated in Fig. 3, a resistor R_{PTAT} is positioned beneath the emitter of transistor B_5 . The voltage across the resistor can be determined as the base-emitter voltage difference between transistors B_5 and B_6 [14], as given by:

$$V_{PTAT} = V_{BE_6} - V_{BE_5} = V_T \ln \frac{N_5}{N_6}, \quad (9)$$

with N_5/N_6 denoting the size ratio¹ between the two transistors B_5 and B_6 . The term $\ln \frac{N_5}{N_6}$ defines the thermal sensitivity of the PTAT current source.

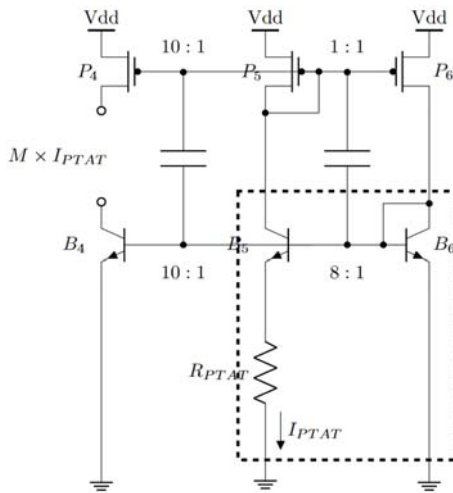


Fig. 3. PTAT current source schematic circuit. The transistor B_5 is eight times larger than the transistor B_6 . The R_{PTAT} resistor plays the role of converting the V_{PTAT} into current through the current mirror $B_5:B_6$. On the other hand, the PMOS P_4 and the transistor B_4 are used to amplify the current by a factor of 10.

The current through R_{PTAT} can then be derived as:

$$I_{PTAT} = \frac{k_B T}{q R_{PTAT}} \ln \frac{N_5}{N_6} \quad (10)$$

Equation (10) distinctly emphasizes the direct proportionality of I_{PTAT} with temperature. Due to the logarithmic nature, excessively increasing the ratio N_5/N_6 is not beneficial. A ratio of 8 is employed in our design to obtain the $\ln 8 = 2$ factor.

3.3. CTAT and PTAT Current Subtraction

The currents supplied by the CTAT and PTAT current sources exhibit slopes with opposite signs

(Fig. 4) they can be combined to be subtracted in a load resistor. The resistances R_{PTAT} and R_{CTAT} can be tuned to optimize temperature sensitivity while nullifying the current offset at a specified temperature. This can be represented by the equation:

$$\Delta I = M \times (I_{PTAT} - I_{CTAT}) \quad (11)$$

The comprehensive circuit is depicted in Fig. 6, where R_{L+} and R_{L-} denote the readout load. P_3 and P_4 amplify the two currents by $M = 10$ before subtraction. This multiplication is feasible because the readout occurs after offset subtraction. Otherwise, the offset would considerably diminish the dynamic range. The M multiplying factor directly enhances temperature sensitivity, as demonstrated in Fig. 4 and Fig. 5.

3.4. Circuit Simulation with Cadence Virtuoso

In addition to formulating the analytical model based on the background outlined in the CTAT and PTAT sections, it is imperative to conduct simulations to validate our circuit design. The simulation employs device models from the IHP130 nm library, closely resembling the practical devices used in fabricating the ASIC. DC analysis is performed with temperature variations. This simulation serves the dual purpose of validating the developed model and delineating a suitable "range" for unknown parameters/operations, referred to as "empirical parameters."

4. Results

The circuit depicted in Fig. 6 has been simulated utilizing IC CAD tools (Cadence Virtuoso), demonstrating the anticipated linear progression of I_{PTAT} and I_{CTAT} with temperature across an extensive temperature range from -150°C to 150°C .

Fig. 4. shows the comparison between the temperature dependencies of I_{CTAT} and I_{PTAT} as analytically predicted, employing IHP130 BiCMOS ASIC technology. Setting $R_{PTAT} = 280\ \Omega$ and $R_{CTAT} = 6.25\ \text{k}\Omega$ these currents intersect at approximately 50°C and demonstrate comparable slopes (in absolute value) of about $0.5\ \mu\text{A}/^\circ\text{C}$.

Finally, the configuration in Fig. 6 illustrates the method to subtract (equation (11)) the two currents, magnified by 10, resulting in a differential current flowing out from the ASIC into two resistor loads, R_{L+} and R_{L-} . A central-tap connected to the common mode voltage reference $V_{CM} = V_{DD}/2$ enables the receiver to set the common mode voltage of the differential signal. This technique decouples the common mode of the thermometer readout from the ASIC common

¹ In practice, different sizes of transistors are obtained by putting elementary transistors in parallel. Thus, N_5 and N_6 are the number of transistors connected in parallel.

mode, preventing noise contamination during the transmission process.

Minor deviations from the simulated output signal (depicted in black in Fig. 5) to analytical or simulated signals multiplied by 10 reveal non-idealities of the output current mirror. These non-idealities originate from both higher common-mode operation and extreme-temperature environments.

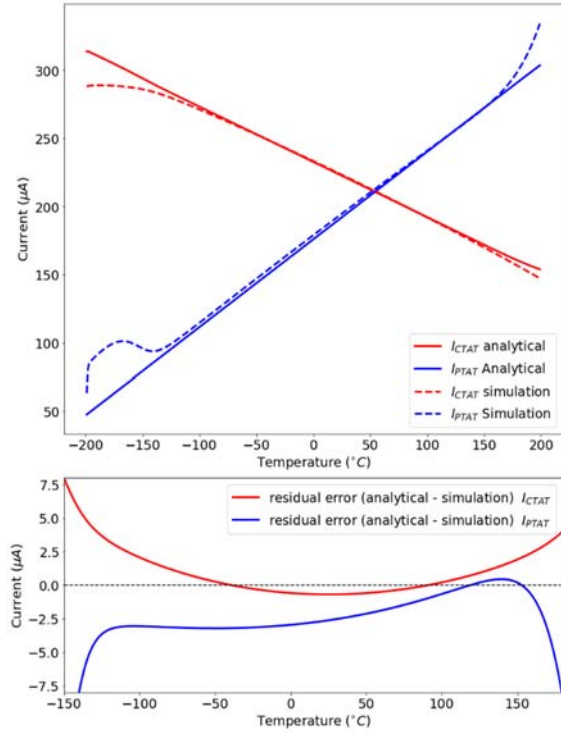


Fig. 4. I_{PTAT} and I_{CTAT} vs. temperature from $-200^{\circ}C$ to $200^{\circ}C$. Residuals between analytical results and simulations show non-linearity at temperature below $-150^{\circ}C$ and above $150^{\circ}C$.

5. Discussion

The linear relationship between output current and temperature within the range from approximately $-150^{\circ}C$ to nearly $150^{\circ}C$ is illustrated in Fig. 5 and Fig. 6. A strong agreement between model and simulation is found in this temperature range. A significant deviation appears outside this temperature range.

The analytical model is based on the fundamental temperature dependencies of SiGe material (simplified for clarity). However, the model tends to overlook practical effects arising from the design, such as parasitic resistances, which are included in the simulations. These resistances can impact the temperature of ASICs, and their influence becomes more pronounced with increased design density, particularly under high voltage or current conditions. This section will focus on discussing factors that could cause the discrepancy of the analytical model compared to the simulation results.

Three reasons can be the cause of this:

1. Simulations made out of specified temperature range (linear model, extrapolation);
2. Analytical model does not consider high order thermal dependencies and neglect dependencies only significant far from room temperatures;
3. The thermometer schematic is optimized around room temperature (setting point: crossing 0 at $50^{\circ}C$) leading to non-optimal operating point far from this temperature. Moreover, such thermometers with differential output provide a larger output current far from the setting point. Larger output current than 1 mA can lead to enhanced nonlinearities.

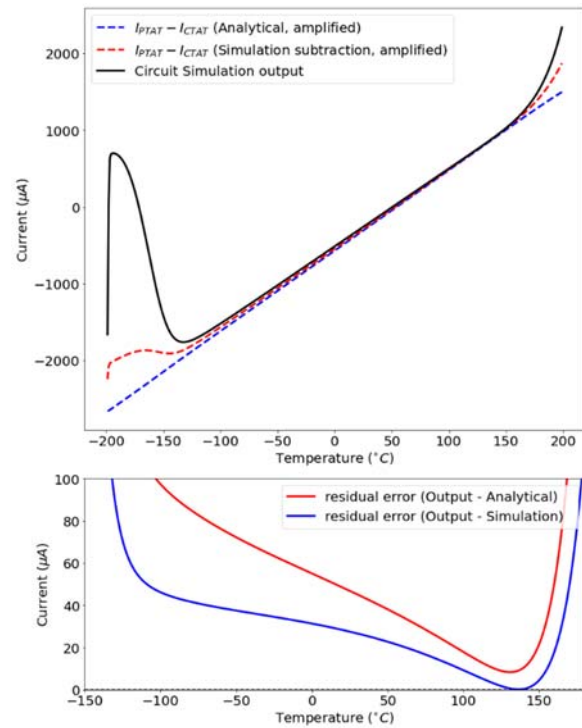


Fig. 5. Top: Differential output current of the thermometer flowing through the R_{L+} and R_{L-} loads (depicted in black) showing the $10 \mu A/^{\circ}C$ temperature sensitivity of this on-chip thermometer; the subtraction of the current I_{CTAT} and I_{PTAT} multiply by factor of 10 for comparison with the output signal: analytical result (red) and simulations (blue). Bottom: The discrepancy between the output and the analytical expression (red), and between the output and the simulation (blue), both have been multiplied by 10.

5.1. Transistor Model Specified Temperature

Simulations exhibited in Fig. 5 and Fig. 6. are done using the IHP design KIT which procures transistors model. These models NPN 13v2 are made for a typical use around room temperature. However, even if $-200^{\circ}C$ and $200^{\circ}C$ are far from the usual temperature operation of an ASIC, the observed deviations are probably not only due to the transistor model.

5.2. Simplified Analytical Expression

Deviations between the analytical model and simulation can be due to non-representative simulation or analytical models. Indeed, we describe in this paper the ingredients of our analytical model, which could be improved by including parasitic resistances, non-ideality factors, self-heating, etc.

5.3. Nonlinearities Far from Setting Point

For a given R_{PTAT} and R_{CTAT} , the thermometer is set to provide zero differential current at a given temperature; here, 50 °C as illustrated in Fig. 5. Far from this setting point, the current in the circuit starts to be unbalanced, until even becoming zero on one branch. This seems the most credible reason of the saturations at output current $> |2\text{mA}|$ of the thermometer.

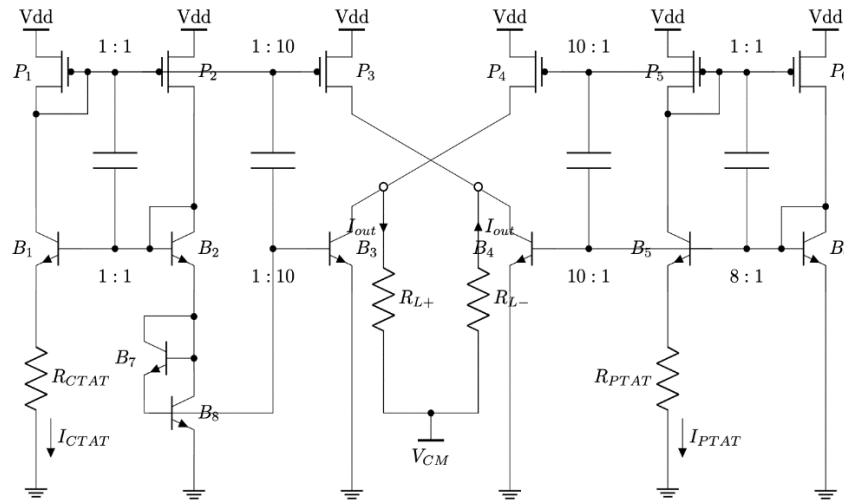


Fig. 6. Thermometer schematic including the PTAT (right), CTAT (left) and crossing bridge subtracting the currents (middle).

6. Conclusion

The suggested on-chip thermometer exhibits a linear response across an extensive temperature range from -150 °C to 150 °C. The sensitivity of this thermometer is adaptable through modifications in the M factor, R_{PTAT} , and R_{CTAT} values. Additionally, the zero offset temperature is adjustable by varying the ratio R_{PTAT}/R_{CTAT} . This enables the optimization of the temperature range centered around a specific temperature. This paper introduces a set of parameters enabling coverage of up to a 300 °C range around 50 °C.

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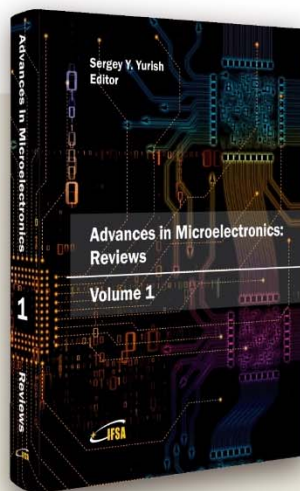


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IMU Data-based Recognition for Sports Exercises: An Enhanced Distance Optimization Approach for Repetition Counting across Activities

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Abstract: In the field of human activity recognition (HAR), inertial measurement units (IMUs) are a commonly used method to record movement patterns. In the study presented in this paper, IMU captured seven different sports exercises performed by 21 participants. In the preliminary data analysis phase, an exercise classification was conducted using the Long Short Term Memory (LSTM) Network and Temporal Convolutional Network (TCN). The LSTM achieved an accuracy rate of 94.2 % for training and 90.8 % for testing. Similarly, the TCN demonstrated rates of 95.5 % for training and 91.6 % for testing. The subsequent stage was centered on quantifying the number of completed repetitions. A distance value was derived which showed promising results for exercise-independent counting without the need for manual feature selection. For further improvement, a range-to-mean ratio of the standard deviation was calculated and used for feature selection. Combined with a local extrema analysis of the modified distance values the accuracy of counting repetitions was significantly improved, especially for exercises that show irregularities in the signal course.

Keywords: Human activity recognition, Inertial sensors, Artificial neural networks, Repetition counting, Distance, Local extrema analysis

1. Introduction

Inertial Measurement Unit (IMU) sensors, in combination with broadband technologies and high-performance algorithms, offer great potential in the detection, monitoring and improvement of sports exercises. Especially in times of a lack of trained specialists and the demands resulting from the increasing individualization of personal leisure time, digital therapy and training methods are needed for both the physiotherapy and fitness markets. Typically,

methods of supervised learning are predominantly used in the field of human activity recognition (HAR). The most common approaches in the literature are those based on the Support Vector Machine [1-3], followed by Naive Bayesian [4, 5] and k-nearest Neighbour [6]. Less common are deep learning approaches using Convolutional Neural Networks (CNN) [7] and Long Short Term Memory (LSTM) Networks [8]. Unsupervised learning methods are the exception and have so far only been used to count the number of repetitions, for example in tennis strokes

[9]. The work is based on preliminary work [10, 11] on supervised learning of three sports exercises, where high accuracy was achieved with both the classifiers and the neural networks used. The workflow included data acquisition and preprocessing, the training of Artificial Intelligence (AI) models, the optimization of model parameters and a final evaluation of model performance.

This study aims to choose, optimize and compare model structures and parameters for supervised learning using an extended database. The database consists of recordings of seven different sports activities performed by 21 participants. Another focus of this paper is the development of a universal counting algorithm suitable for counting repetitions of any sports activity.

2. Data Generation and Preprocessing

Within the study with 21 participants, 7 different exercises were completed at one sports device as successive set. The execution of the different activities is shown in Fig. 1.



Fig. 1. recorded exercises on the sports device, 1-support, 2-squats, 3-dips, 4-lunges, 5-pull ups, 6-sit ups, 7-push ups.

The exercises support, squats, dips, lunges, pull-ups, sit-ups and push-ups were recorded as continuous recordings with IMUs at the positions of chest, hand and foot. With a set sampling rate of 30 Hz, the quantities of linear axial accelerations, rotation rates, orientations (Euler angles, quaternions, magnetic flux densities), absolute pressure and the Cartesian position in space were captured. The time series were labelled during the recording process by switching the subjects between pause and activity

intervals using a wearable device. In total, around 230 minutes of exercise data were recorded, divided into 24 exercise sets, which also included intervals of stretching and loosening exercises, labelled as pauses. Signal interruptions that occurred were linearly interpolated during data pre-processing and the time series of three IMUs were synchronized. The distribution of the generated motion data to the different classes is shown in Table 1. As can be seen from this, about half of the total amount of data belongs to the pause intervals. Despite the comparatively high volume of seemingly unnecessary data, it was fully utilized for model training to achieve the ability to distinguish between pause and active intervals.

Table 1. Distribution of classes in the used database.

Class	Lunges	Dips	Pull-ups	Squats
# Samples	38997	22675	21736	32288
percentage [%]	9.39	5.46	5.23	7.77
Class	Push-ups	Pauses	Sit-ups	Support
# Samples	21958	220290	32544	24816
percentage [%]	5.29	53.04	7.84	5.98

3. Training, Optimization and Comparison of KNN

The supervised models were trained in MATLAB R2022b. At first, the number of input variables was reduced to 36 by using only the linear accelerations, rotation rates, magnetometer data and Euler angles. Also, the data were divided by segmentation to be able to process the time series as sequential data in MATLAB. To ensure a diverse distribution of unbalanced data across the training and holdout validation sets, a segment length of 500 samples was chosen (corresponding to approximately 16 seconds of workout time). The holdout ratio was designated as 0.3, resulting in the generation of 582 sequence blocks for training data and 249 blocks for validation data. Subsequently, a LSTM- and a CNN network were trained and an optimization of the hyperparameters was carried out. The CNN network can be described as a temporal convolutional network (TCN), which consists of several CNN blocks connected in series. The time series are scanned in the form of a receptive field, the extent of which is influenced, for example, by the number of blocks. [12] The most accurate models are compared in Table 2 with the accuracies achieved and the training times required. The TCN could be trained more than three times as fast as the LSTM with slightly better accuracy.

Fig. 2 shows the obtained confusion chart for validating the TCN. One possible reason for incorrect assignments after the optimization of the hyperparameters can be justified with the applied methodology for labelling the data. In this study, the

test persons independently initiate the beginning and end of an exercise interval by operating a wearable, implying that the activity ranges are not uniformly defined. This can be observed in the false positives and false negatives elements of the pause class, which contain significantly more samples than the other classes. This effect was already reduced by the implementation of a three-second countdown between the actuated switch-over point and the beginning of the exercise execution. However, deviations remain, especially in exercises where the starting position can only be assumed after the wearable has been activated (e.g., pull-ups and dips).

Table 2. Comparison of the trained LSTM and TCN structures with the highest accuracies.

Model	Normalized training time	Accuracy		Worst F1-score (class)
		Training	Validation	
LSTM	100 %	94.2	90.8	83.8 (pull-ups)
TCN	28 %	95.5	91.6	83.4 (pull-ups)

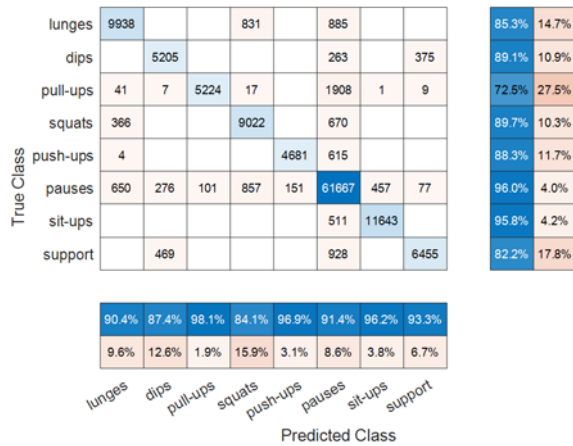


Fig. 2. Confusion matrix for applying the trained TCN on the validation data.

Furthermore, it must be taken into consideration that the subjects were largely unrestricted in their exercise execution. Different variations were tolerated, e.g., squats with stretched or bent arms and simplified executions (e.g., pull-ups in inclined posture). Even though some exercises have a high degree of similarity (e.g., lunges/squats, dips/support), inter-activity mismatch is limited. Fig. 3 shows the TCN model predictions for a section of the validation dataset. There are occasionally false assignments, which were filtered out by post-processing. In the smoothed prediction that is also shown, a sliding window of 50 samples was used to determine the dominant class in each window, which slightly improves the overall accuracy of the validation by additional 0.4 %.

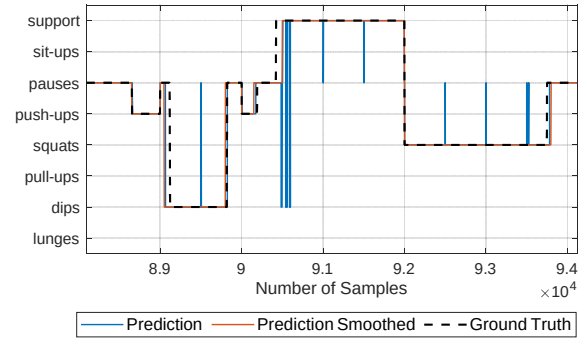


Fig. 3. Time course of the TCN model predictions for a segment of the validation data, comparing model prediction (non-smoothed/smoothed) and ground truth.

4. Repetition Counting

The execution of repetitive exercises is visible as a periodic progression of individual measured variables, which differ in type and curve progression depending on the respective type of exercise. To reduce the data load and to improve the generalizability of the implemented algorithms, the strategy was to use only variables that are independent of the orientation and position of the subjects. Therefore, only the values of the axial accelerations and rotation rates were considered. Consequently, 18 measurement variables were used to determine the number of completed repetitions. As the value ranges of the inertial measurement variables are widely distributed, symmetrical normalization was applied to all variables in the interval $[-1 \dots +1]$.

To enable an evaluation of the counting algorithm without the influence of an upstream model for classification, ground truth labels were used for the development of the counting algorithm. It is also important to mention that only the activity intervals in their chronological order from the recording were used as the data basis for the analysis. This order of data would also be present in a potential interconnection of the model and counting algorithm when the latter receives sequences of predictions by the classification model. Consequently, 24 sets in total were analyzed in series by the counting algorithm.

The special requirement in this work was to find a parameter that shows an oscillating course for a variety of different sports exercises. Such an exercise-independent parameter can be calculated with the distance Dis between a pattern segment A and every segment B of the respective activity as described in equations (1) and (2). C is the difference between A , B and Dis represents the summed amounts of C . A and B are matrices with the dimension $m \times n$, where m defines the number of samples, also called segment length and n is the number of features for one segment.

$$C = A - B = \begin{bmatrix} a_{11} - b_{11} & \dots & a_{1n} - b_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} - b_{m1} & \dots & a_{mn} - b_{mn} \end{bmatrix}, (A, B \in \mathbb{R}^{m \times n}), \quad (1)$$

$$Dis(A, B) = \sum_{i=1, j=1}^{i=m, j=n} |c_{ij}| = \sum_{i=1, j=1}^{i=m, j=n} |a_{ij} - b_{ij}| \quad (2)$$

The pattern segment was selected in the centre of each exercise interval to avoid the influence of transition areas between other classes because, as previously mentioned, it was not possible to precisely define the start and end points of an exercise execution. After the segment length was set to 30 samples, the distances for all segments of an activity interval were calculated with a step size of one sample. The obtained distance values were smoothed by a moving average filter with a bandwidth of 15. Additionally, the median was calculated for each interval of smoothed distance values. The courses of unfiltered/filtered distances and the median values are presented in Fig. 4 for an exemplary execution of six pull-ups. The oscillating distance curves represent the number of completed repetitions. A characteristic attribute is that the distance increases significantly at the borders of an interval to be examined. In addition, the distance in the area of the pattern segment becomes zero. To count the repetitions, the number of intersections at the falling edge of smoothed distance values and the median were analyzed (red crosses in Fig. 4).

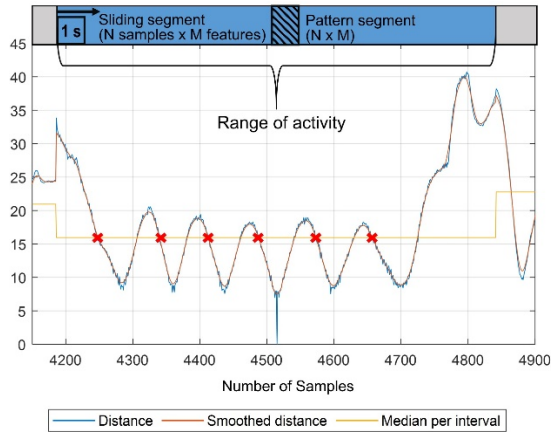


Fig. 4. Calculated distance values for the execution of six pull-ups, marking the counted intersections with the median at the falling flank ($N = 30$, $M = 18$).

To evaluate the accuracy of the counting algorithm, the deviation rate and the class-wise deviation rate were used, as described in (3) and (4). The deviation rate δ is signed and thus enables the assessment of whether too many or too few repetitions Rc have been counted in an exercise set. When determining the class-wise deviation rate δ_{class} for n records, the amounts of the individual deviation rates are calculated. All deviation rates are relativized by multiplying with the true number of repetitions Rt .

$$\delta = \frac{Rc - Rt}{Rt}, \quad (3)$$

$$\delta_{class} = \frac{\sum_{i=1}^{i=n} Rt_i \cdot |\delta_i|}{\sum_{i=1}^{i=n} Rt_i} \quad (4)$$

To obtain a final value for the overall performance of the counting algorithm for a larger number of trials, δ_{SUM} was calculated with the weighted average of δ_{class} , considering the overall distribution of the m activity classes and shown in equation (5). There n_m is the number of samples of each activity class and n_A is the number of all activity samples.

$$\delta_{SUM} = \frac{\sum_{i=1}^{i=m} \delta_{class} \cdot n_m}{n_A} \quad (5)$$

Table 3 shows the results of experiments for optimizing the counting algorithm by varying the features and the segment length for distance calculation. First, the features were varied, using a segment length of 30 samples. The deviation rates listed (class-wise and weighted average) suggest that the accelerations (acc) have a significantly higher influence on successful repetition counting than the gyroscope data (gyro). The lowest δ_{SUM} was determined with a combination of rotation rates and accelerations and was therefore defined as the feature setting for further investigations. The lower part of Table 3 shows the results of varying the segment length, i.e., the number of samples used to calculate the distance. The range of samples was adjusted from 20 to 70, and the most optimal outcome was achieved using the previously employed 30 samples. There was a slight incremental enhancement of 0.7 % for δ_{SUM} , observed when utilizing a segment length of 50 samples.

Table 3. Results of optimization experiments, determine the deviation rates for the activities (1-support, 2-squats, 3-dips, 4-lunges, 5-pull ups, 6-sit ups, 7-push ups) and the overall deviation.

	δ_{class} in %							δ_{SUM} in %
	1	2	3	4	5	6	7	
variable feature selection, segment length = 30								
acc + gyro	21.2	2.8	19.3	15.0	9.1	2.9	7.9	10.8
acc	18.6	8.3	14.6	13.4	7.5	5.2	9.0	10.9
gyro	38.3	3.9	34.8	58.1	28.6	11.7	10.7	27.5
variable segment length, features: acc + gyro								
20	19.7	4.4	21.5	23.5	12.1	7.3	9.0	14.0
40	23.9	3.0	19.3	14.2	8.5	2.6	7.3	10.8
50	23.9	3.0	15.9	12.4	9.6	2.3	7.3	10.1
60	23.1	3.0	16.7	12.4	14.6	2.6	7.9	10.8
70	26.1	2.8	19.3	13.7	14.6	3.5	9.0	12.0

For the detailed consideration of the class-wise differences, these two mentioned tests are considered (highlighted grey in Table 3). In both cases, the δ_{class}

was most significant for the support class with 21.2 % and 23.9 % respectively. In contrast, the classes squats and sit-ups were the most reliably counted by far with δ_{class} between 2.3 % and 3 %.

To analyze possible causes for the partly very different values of δ_{class} , the deviations for each of the 24 recorded sets were considered for the upper, highlighted parameterization in Table 3. Occurring δ with a modulus greater than 0.3 were examined in more detail. Typical scenarios for exceeding and falling below the true number of repetitions were identified from different recordings and are presented below.

In Fig. 5 top left, the performance of squats is shown where the exercise execution was varied within the interval. Consequently, the median value in the immediate vicinity of the pattern segment is notably elevated, leading to a lack of intersections with falling edges within this specific area. Similar characteristics are observed in the upper right portion of the figure, where multiple repetitions of dips toward the end of the interval were also not detected any longer. In the lower part of Fig. 5, too few dips were recorded in the left example. Here, the recognizable periodic progression of the distance values was comparatively short, which suggests only a short execution within the labelled active interval. In the fourth example (bottom right), the two completed repetitions of the support exercise cannot be identified in the progression. One interpretation is that the exercise was performed very irregularly, it is also possible that the test person was physically overloaded. Finally, it can be stated about the evaluation of the faulty intervals that the implemented methodology is particularly susceptible to errors when exercises are performed irregularly. The observation that irregular execution is caused by physical overstress among the test subjects is supported by a dependable analysis of relatively simple exercises, like squats and sit-ups. A special status is occupied by the lunges, whose execution (step position of left and right foot alternately or identical for several repetitions) was not exactly defined, which indicates that the sensor attached to only one foot does not contribute to a periodic progression of the distance values for all movements.

Fig. 5 indicates that achieving an accurate counting of repetitions in an interval is critically dependent on a consistent execution of the exercise, which is not always given in reality. Further refinement of the current approach is required to count varied exercise performances in an interval. The analysis of axial sensor data reveals that only a subset of inertial measurement variables is affected by variations in the exercise execution. For example, in Fig. 6 two different acceleration signals are shown while performing 14 squats (example top left in Fig. 5). While the z-acceleration of the chest sensor za_1 shows a homogeneous course, clearly different movement patterns were recorded for the x-acceleration of the hand sensor xa_2 , which can be justified by changing the guidance of the arms during exercise execution. In the context of universal exercise

monitoring, these in-between executions should also be counted correctly. Highly irregular signals have to be identified depending on the exercise and should be excluded for an improved distance calculation. The standard deviation was determined for the measurements of za_1 and xa_2 . The window size for calculation was set to 90 samples with an overlap of 50 % to have the best representation of the differences between the signals.

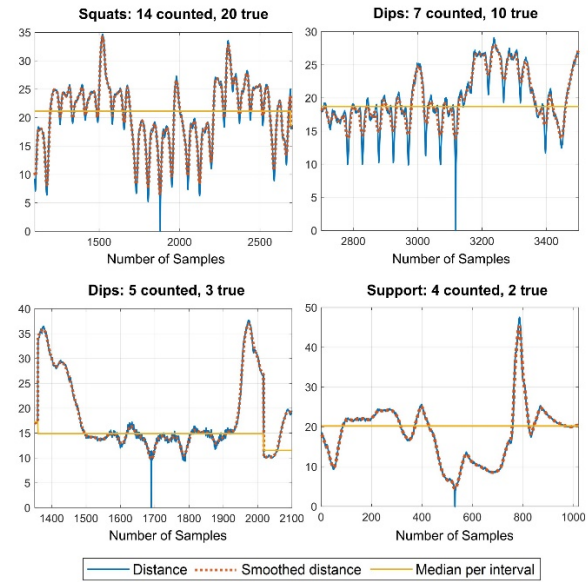


Fig. 5. Progressions of the distance values for incorrectly counted repetitions, top: lower deviation to the true number of repetitions ($\delta < 0$), bottom: exceeding true repetitions ($\delta > 0$); respective indication of the type of exercise with true and counted repetitions.

In the lower part of Fig. 6, the calculated standard deviation of xa_2 shows a much more fluctuating course compared to za_1 . In the context of automatic sorting of the measured variables according to their homogeneity, the range-to-mean ratio k_{R2M} was introduced for the description:

$$k_{R2M} = \frac{\max(data) - \min(data)}{\text{mean}(data)} \quad (6)$$

Calculating k_{R2M} for the standard deviation of the two measured variables to be compared yields around 0.3 for za_1 and 1.7 for xa_2 . The significantly larger value for xa_2 describes the fluctuating signal course, which means that k_{R2M} is well suited for the interval-wise assessment of a measured variable. If, in comparison, only the standard deviations of the measured variables were determined over the entire interval, they would differ significantly less from each other with 0.0687 for za_1 and 0.0717 for xa_2 .

To examine the trend in distance values for reduced feature settings, k_{R2M} of all 18 features were determined for each interval and the features were sorted by descending k_{R2M} . In Fig. 7, the considered

squat interval is shown comparatively for 18 features and a feature set reduced to 12 and 6, respectively, where the features with the lowest k_{R2M} were selected for the reduction. Also plotted are the determined repetitions by the number of intersections with the median at the falling flank. It is apparent that with an increasing exclusion of features with a high k_{R2M} factor, a homogenization of the distance progression is achieved. As a result, the repetitions located in the middle section are aligned to the level of the median and are consequently captured via the intersections that occur. Thus, the delta to the 20 performed squats is reduced to ± 1 recorded repetition.

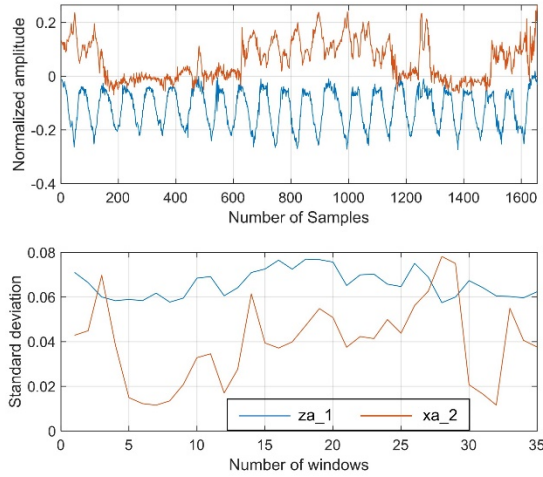


Fig. 6. Comparing the acceleration signals for a miscounted squat interval (top) and their standard deviations for a window size of 90 samples and 50 % overlap (bottom).

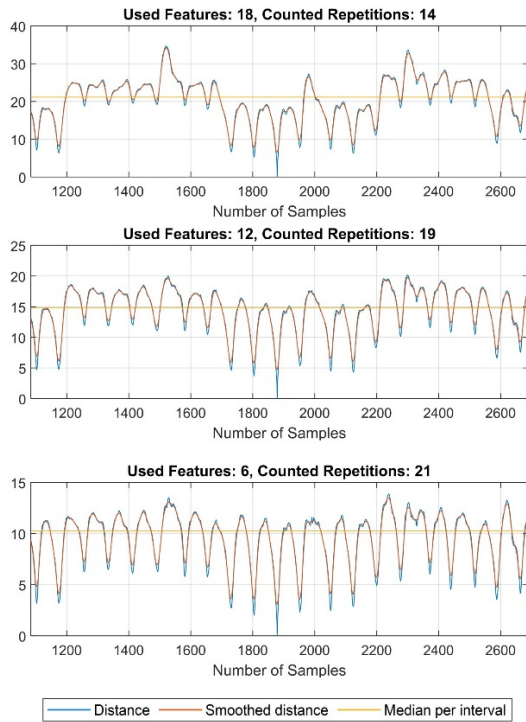


Fig. 7. Homogenizations of the distance with feature reduction based on an ascending sorting according to its range-to-mean ratio.

Table 4 presents the mean deviation rates for the reduction of features from 18 to 6 stepwise. The improvement in performance for counting squats (2) can be achieved except for $N_{\text{Features}} = 15$. Likewise, the deviation rates of sit ups (6) and push ups (7) remain at a low level. However, a significant decrease in counting performance is observed for the other exercises, which also increases δ_{SUM} . In the set-by-set analysis of the incorrect classes, it was recognized that the deviations were almost entirely due to exceeding the true repetitions. The described smoothing of the distances causes all motion patterns to be homogenized. However, the homogenization does not always ensure that the calculated median is at an optimal level for counting the intercepts. This effect can also be observed in Fig. 5 and occurs frequently with poorly counted activities, as a result of too many intercepts being detected with the median.

Table 4. Deviation rates for a feature reduction based on an ascending sorting according to its range-to-mean ratio.

N_{Features}	δ_{class} in %							δ_{SUM} in %
	1	2	3	4	5	6	7	
18	21.2	2.8	19.3	15	9	2.9	7.9	10.8
15	23.1	3.2	22.3	16.5	11.6	3.2	7.3	12
12	28.4	1.4	17.2	25.6	14.1	2.9	7.6	13.9
9	28.4	2.5	17.6	23	21.6	4.1	6.8	14.5
6	37.1	1.9	21.9	26.9	24.6	3.8	8.8	17.3

At this stage of processing, it was checked whether other characteristic points in the course of the distance can be used as incremental conditions for counting. When considering the distance values, it is obvious to check the number of the local extrema points. MATLAB offers the possibility to evaluate the number of local minima points via the command *islocalmin*. [13] The number of local minima can be limited by the parameter minimum separation and was set to 20 samples for the present data, which requires at least 0.67 s in between two repetitions.

In addition to the locations identified as local minima, the prominence is also an output for each minimum. In topography, the prominence describes the independence of a summit. [14] In the present application, it is used to depict the relevance of one local minimum in comparison to other local minima. To calculate the prominence, it is necessary to identify adjacent intervals, which involves applying a horizontal auxiliary line to the local minimum. Then, in both directions, the intersection points of the auxiliary line are defined as boundaries of the upper and lower intervals. These can be intersections with other minima or, if none exist, the start/end points of the signal. Finally, the highest peaks in both intervals are determined, and the smaller one is defined as the reference level. The distance between the reference

level and the local minimum finally describes the value of the prominence.

Using the prominence metric allows for additional refinement in the identification of minima, potentially by setting a threshold that determines the minimum value the prominence must surpass, thus further constraining the number of identified minima. For this purpose, the approach of a scalable limit was used by scaling the maximum of the prominences of an interval with a value smaller than 1. For a scaling factor of 0.3, the local minima shown in red in the following Fig. 8 were obtained. These represent the iterative execution of dips in the example shown. In contrast, without the limiting prominence threshold, too many minima (shown in blue) are detected and would not result in a good counting performance. In other words, by limiting with a scale factor of 0.3, the number of minima counted was reduced from 9 to 4 in the shown dip exercise section of Fig. 8. Based on the preliminary considerations, the counting performance for different parameterizations of the prominence scaling factor in combination with varying feature settings, based on the preselection by increasing k_{R2M} , was subsequently tested. Table 5 summarizes the results for the obtained δ_{SUM} .

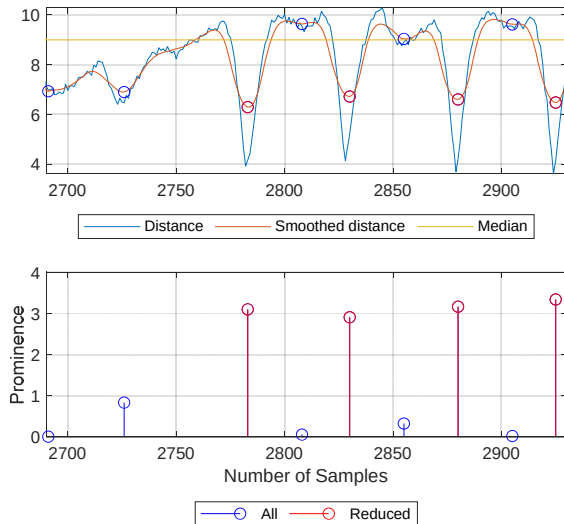


Fig. 8. Segment of a dip interval with feature-reduced distance ($N_{Features} = 9$), indicated local minima and their according prominence ($minSeparation = 20$) and reduced number of minima with prominence $\geq 0.3 \cdot \max$ (prominence).

First, the impact of the scaling factor was assessed in the range of 0.2...0.5 for $N_{Features} = 9$. It was detected that a value of 0.2 was the most effective setting, which was also verified for $N_{Features} = 12$. When the value was < 0.2 , too many minima were used for counting, while with a scaling factor > 0.2 , there was a tendency towards too few counted repetitions. Once the optimal scaling factor was determined, various feature settings with a size of 6 to 18 features were tested. 18 features correspond exactly to the size of the measurement variables selected at the beginning,

without additional feature selection based on k_{R2M} . To ensure comparability, the original feature setting, including axial rotation rates and accelerations, was retained.

Table 5. Overall deviation rates for different scale factors and feature sizes.

Scale factor	NFeatures	δ_{SUM} in %	Comments
0.1	9	16.1	Testing different scale factors for constant feature setting
0.2	9	8.8	
0.3	9	10.1	
0.4	9	14.2	
0.5	9	20.3	Validation of scale = 0.2 for another feature setting
0.2	12	10.2	
0.3	12	10.9	
0.2	6	11.1	Testing different feature settings with constant scale factor
0.2	12	10.2	
0.2	15	8.7	
0.2	18	10	
0.3	15	14.3	NFeat = 15 showed unfavourable performance

The results showed reduced variability, hovering approximately at 10 %. Furthermore, testing 15 features revealed a remarkably low deviation rate of 8.7 %, in addition to the nine features that had been tested previously. Nevertheless, a different test revealed a substantially worse performance with 15 features and a scaling factor of 0.3. Consequently, it can be assumed that of the parameters tested, $N_{Features} = 9$ and a scaling factor of 0.2 give the most reliable results.

When considering the class-specific deviation rates, a comparable influence of the scaling factor on almost all classes was found, which is shown below in Fig. 9.

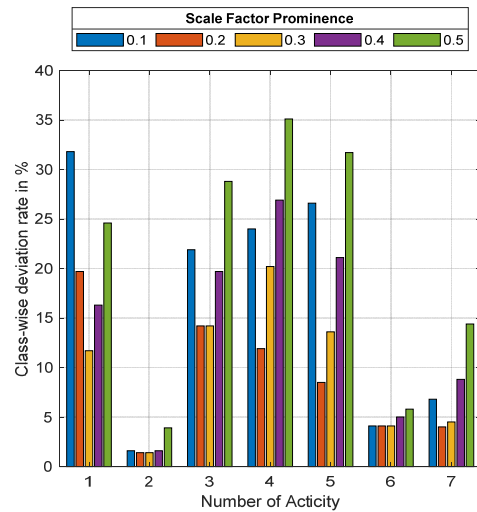


Fig. 9. Class-wise deviation rates for varying scale factor between 0.1 and 0.5.

The deviation rates show a minimum at a scaling factor of 0.2 to 0.3 and increase accordingly for other values. Squats and sit ups are the exercises that have the lowest deviation rates and consequently show a more robust behaviour with a wider range of scaling factor values. The impact of the number of features was also taken into account, but no distinct trends were evident in this analysis. It is reasonable to assume that with an increased quantity of input variables, discernible trends might emerge. Nonetheless, this aspect was not further explored to maintain consistency with the previous results for the sake of comparison.

5. Discussion and Conclusion

In the presented work, recorded IMU data consisting of seven sports activities were examined. The first step was to classify the completed exercises using supervised machine learning methods. Two different network structures (LSTM and TCN) were trained and the hyperparameters of the models were iteratively optimized. The TCN model gave a good performance with 91.6 % validation accuracy using significantly shorter training times. One way to improve the accuracy of the prediction is by post-processing the labels generated during recording. This will enable a more accurate determination of the neat duration of the exercise, as it has been shown that the dominant percentage of misclassifications is caused by confusion of the break class with other activities. For further investigations, the interconnection of several classification levels would be another possible approach to further increase the model accuracy. For post-processing of the model predictions, a smoothing algorithm was applied that determined the dominant prediction class using a filter width of 50 samples. Although the overall accuracy of the prediction was only slightly improved to 0.4 %, the described procedure can optimize the user experience in possible applications for real-time recognition.

The second crucial aspect of the study involved developing an algorithm to count completed exercise repetitions. By calculating distance values for a pattern segment defined within an exercise interval, the number of repetitions could be made detectable for all activities based on this one parameter, which made the class-specific analysis of individual signal variables unnecessary. To count the repetitions, the intersections of the distance values with the median of all distances of a single exercise phase were evaluated. For performance evaluation with different parameterizations (segment length, input features), the deviation rate was introduced. The implemented algorithm performed well when counting regular executions and less effectively if the distance of an interval does not show a homogeneous, periodic course. In order to accurately quantify these exercises, the measured variables were arranged based on their regularity using a range-to-mean ratio of their standard

deviation. Subsequently, the distances were recalculated with reduced feature compositions. A significant improvement in counting performance was finally achieved by switching to the evaluation of local minima. Through additional parameters such as the prominence, the average total deviation rate could be reduced to 8.8 %. Nevertheless, even with the optimizations carried out, irregularly performed exercises cannot be counted correctly in every case. If, however, the uniform execution is observed within an interval, the optimized distance value method provides reliable counting results. The key advantage of the counting algorithm is its ability to load a new pattern segment as a reference for each new exercise interval, resulting in a highly robust algorithm capable of accommodating different people and their specific types of exercise execution.

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**ADVANCES IN SENSORS:
REVIEWS**

2

Sergey Y. Yurish
Editor

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Radiation Degradation Individual Peculiarities of γ -irradiated Discrete Low Power Thyristors, Manufactured on Si and SiGe

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Abstract: Radiation degradation during γ -irradiation of discrete low-power thyristors, both control (Si) and investigated SiGe-fabricated, is a complex nonlinear process that is individual for each device. It is possible to distinguish three γ -irradiation ranges, in which the degradation of the average holding current for control and investigated thyristors proceeds in different ways. For $D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^2$ mSv there is a decrease in $I_h(D_\gamma)$ for control Si devices, possibly connected with the "low-dose effect"; for SiGe devices, there is an increase in the holding current, therefore, no "low dose effect". Range $D_\gamma \approx 1 \cdot 10^2 \dots 1 \cdot 10^4$ mSv can be considered as an area of unstable operation of the control thyristors in the γ -radiation field, devices made with SiGe are sufficiently more stable. For $D_\gamma \geq 1 \cdot 10^4$ mSv there is an expected increase in $I_h(D_\gamma)$ for Si thyristors, devices, manufactured with SiGe continue to be more stable. When $D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^4$ mSv use of SiGe makes it possible to increase the average interval radiation resistance of thyristors by approximately 7 %, and in the range of $D_\gamma \approx 1 \cdot 10^4 \dots 1 \cdot 10^6$ mSv $\approx$ up to 12 %.

Keywords: Individual nonlinear process, Discrete low-power thyristor, Radiation degradation, Average interval radiation resistance, SiGe.

1. Introduction

Over the next 5-10 years, the abrupt rise of commercial and military interest in space-based systems is foreseen and it includes new launch capabilities, creation of large-scale constellations for communication or earth observation [1]. The distribution of the spacecrafts are approximately as follows: commercial 46 %, government 19 %, military 15 %, civil 7 % and mixed use 13 %. As of the publication of cited report, more than 2000 satellites are in the different orbits (LEO, Low Earth Orbit (160 – 2000 km) – 66 %, GEO, Geostationary ($\approx$ 36,000 km) – 25 %, MEO, Medium Earth Orbit

(2000 – 36,000 km) – 6 %, and HEO, Highly Elliptical Orbit (e.g. 40,000 km apogee) – 3 %). The number of satellites is expected to quintuple by 2030, with 1,100 expected to be launched per year in 2025 alone (almost four times the number launched in 2018). With all this activity, by 2040, the global space industry is forecast to grow up to \$1...2.7 trillion. It may become one of the main world economy branches.

One of the most serious obstacles to the effective functioning of the satellites constellations is so called space weather [2]. The highly hazard variable space radiation environment around Earth can influence the global satellite infrastructure, causing temporary malfunctions or permanent loss of satellite functions.

From the practical point of view, especially important is the LEO radiation situation [3, 4], especially important for the military satellite functions [5], Table 1:

Table 1. Orbits and Tasks for Spacecrafts .

No.	Space Task	Orbit types	Sensors
1.	Optical Remote Sensing	LEO	Optical
2.	Early Warning	GEO, HEO, LEO	Thermal
3.	SAR (Synthetic Aperture Radar) Use	LEO	Imaging radar
4.	Signals Intelligence	LEO, GEO	Radio receiver

Satellites experience a partial or total mission loss directly attributed to radiation effects on electrical components [6]. The radiation situation in general on the orbits shown in [7]. This threat is growing due the fact that the highly developed technological society becomes much more dependent on satellite capabilities [8].

In the MathCAD environment, modeling and forecasting of the complication of the on-board radio-electronic equipment of space vehicles was carried out [9]. The excess quantity of the equipment components, leading to the decrease in the reliability of the spacecrafts was associated with insufficient radiation resistance of the elementary base. Therefore, the main practically important task is the search for technological solutions to increase the duration of the operation of the onboard radio electronic equipment of spacecraft. It was proposed to implement effective technologies into the manufacturing of the on-board electronic equipment for increasing of the apparatus radiation resistance; thus, active electronic elements (discrete transistors, npn structures of the IC, thyristors of the power supply system's etc.) of space vehicles are to be radiation hardened.

2. Radiation Hardness Improvement of the Electronic Element Base: Technological Approach

Radiation hardening covers a wide variety of techniques [10]. The concept of radiation hardening implies robustness but it does not imply total immunity to radiation, only an abatement of radiation effects such that the product will have sufficiently high reliability to fulfill its mission. The method focuses on modifying the baseline semiconductor process to reduce various physical processes that affect radiation sensitivity. This method of mitigation is called radiation hardening by process (RHBP). It can reduce a component failing a radiation metric during test irradiation. In other words, because use of an effect in

the baseline process, manufactured with the modified process elements will pass the metric at the radiation testing. In addition, the main feature. RHBP solutions are expected to have an advantage in that they can make an existing product radiation-hardened (or at least tolerant) without modifying the design, thereby reducing cost and development time. It was the main matter of SiGe use in the well-known technologies.

2.1. Si Doping for the Decreasing of the Radiation Defects Concentration

The creation of semiconductor materials for the manufacturing of radiation-resistant microelectronic and discrete production is a part of the global problem of development, manufacture and application of materials that retain their physical properties under the influence of ionizing radiation [11]. This approach based on the defect engineering strategies [12]. Point electrically active defects that create deep energy levels in semiconductors (impurity defect complexes and/or clusters) thereof are used to control the physical properties of semiconductor materials.

The electrically active A-center (VO) in Cz-Si is the most important defect [13]. It associated with interstitial oxygen O_i (oxygen interstitial atom) and vacancy V. The defect in the crystal lattice resulting from the interaction of Si with high-energy ($\cong$ MeV) particles. A-center forming according to a quasi-chemical reaction in the fields of ionizing radiation due to the generation of diffusing to O_i vacancies. The recombination properties of A-centers (effective traps for injected minority charge carriers in npn and npnp structures) significantly deteriorate the performance of irradiated semiconductor devices.

A number of publications have been devoted to the doping of Si in order to increase its radiation resistance by inhibiting the formation of A-centers. For example, [14] shows that the presence of an impurity of Er ($n\text{-Si}\langle\text{Er}\rangle$) or La ($n\text{-Si}\langle\text{La}\rangle$) in silicon leads to the slowdown in the process of radiation defect formation.

Concentrations of A-centers and E-centers in the irradiated $n\text{-Si}\langle\text{Er}\rangle$ or $n\text{-Si}\langle\text{La}\rangle$ almost an order of magnitude smaller compared to the control irradiated samples. Thus, the presence of erbium or lanthanum atoms in the silicon volume significantly reduces the efficiency of the formation of vacancy-oxygen and vacancy-phosphorus complexes. According to the authors of the work under consideration, the observed decrease in the concentration of these complexes is most likely due to the binding of oxygen atoms with impurities of rare-earth elements in the complexes, as well as the interaction of Er and La atoms with point defects introduced during gamma irradiation.

The processes of formation of radiation defects in silicon doped with dysprosium ($n\text{-Si}\langle\text{Dy}\rangle$), irradiated by γ -quanta ^{60}Co [15]. Monocrystalline n-type conductivity silicon with resistivity $\rho = 10 \dots 65 \text{ Ohm}\cdot\text{cm}$ was used. The content of interstitial optically active oxygen was $5 \cdot 10^{16} \leq N_{O_i} \leq$

$7 \cdot 10^{17} \text{ cm}^{-3}$. Alloying with a rare-earth element (REE) was carried out in the process of growing from a melt. The measurements were carried out by transient capacitive spectroscopy (DLTS) on Schottky barriers. It was shown that the presence of ytterbium atoms in the volume of silicon leads to a decrease in the concentration of A-centers by a factor of 2-6.

In the formation of radiation defects in n-type silicon single crystals (Si<P>) was studied at various levels of doping with transition element impurities [16], Cu, Ni, Ir, Rh, Pt and Au, hereinafter denoted as M. The initial material used was n-type silicon with ρ from 2 to 5 Ohm-cm, grown according to the Czochralski method. Silicon doping was carried out by thermal diffusion from the deposited M layer on the surface of the silicon wafer at 850-1200 °C for ~5 hours. Under these diffusion conditions, all the considered impurities are distributed almost evenly over the entire depth of the samples. All silicon samples were irradiated with γ -quanta of the source Co^{60} up to the dose 109 R. With an increase in the radiation dose, the concentrations of radiation A-centers increase in the doped samples n-Si <P, Rh>, n-Si <P, Pt>, n-Si <P, Au>. Therefore, the use of these impurities to increase the radiation resistance of silicon is not possible.

Measured concentration of A-centers in the n-Si <P, Ni>, n-Si <P, Cu> samples less than in the control Si [17]. The authors of the publication attribute the result to the formation of electrically inactive defects, compounds of metals and oxygen. The last reduce the concentration of O_i in doped Si, due to which it can decrease in the efficiency of A- and K-center formation. In the Si doped with Ni samples, star-shaped defects are observed. Numerous interconnected clusters of nickel atoms exist in the form of specific clusters with the size of 10...15 μm . This excludes the use of this method to increase the radiation resistance of typical microelectronic structures with layer widths $\approx 10^{-1} \mu\text{m}$.

There is no data in the available literature on the use of silicon doped with rare earth elements or transition metals for the manufacture of active IC structures or discrete devices with increased radiation resistance. Perhaps this is because in silicon p-n junctions, when decorating dislocations with metallic impurities, there is an increase in leakage currents up to a short circuit of the junction [18].

2.2. Use of the Isovalent Impurities to Control Radiation Defect Formation in Silicon

The use of SiGe to improve the radiation resistance of silicon has long been seen as an effective method for improving the radiation resistance of a semiconductor material [19]. For Si with germanium concentration $N_{\text{Ge}} = 2 \cdot 10^{20} \text{ cm}^{-3}$ a significant increase in radiation resistance has been achieved, estimated by slowing down the change in the concentration of the main charge carriers. This is considered by the authors

as the most promising silicon technology used for the manufacture of precision detectors used in nuclear radiation fields [20]. The application of isovalent silicon doping (Ge, Pb and Sn) was considered as a major trend in the control of radiation defect formation in Si used for the production of devices with low radiation sensitivity [21].

To suppress the concentration of A-centers, engineering strategies are needed to control defect formation in the material of inhomogeneous active structures of microelectronic and discrete devices [22, 23]. In particular, the use of isovalent impurities (carbon (C), germanium (Ge) and tin (Sn)) to control the formation of VO complexes in Si has been proposed. Isovalent impurities replace Si atoms but are electrically inactive. When they are embedded in the lattice of Si, its elastic stress is created (tensile in the case of C and compression for Ge, Sn and Pb). This is due to the change in its structural and physical properties due to different covalent radii of impurities and the doped matrix. Carbon has the smallest covalent radius $r_{\text{C}} = 0.77 \text{ \AA}$ compared with Si ($r_{\text{Si}} = 1.17 \text{ \AA}$), covalent radius of Ge, $r_{\text{Ge}} = 1.22 \text{ \AA}$. For Sn and Pb $r_{\text{Sn}} = 1.41 \text{ \AA}$, $r_{\text{Pb}} = 1.44 \text{ \AA}$ respectively. The introduction of these impurities into the crystal lattice does not affect the concentration of carriers in Si, but their presence can alter the mobility of the carriers. Isovalent impurities interact with vacancies, e.g., Ge, Sn, Pb – effective stocks for vacancies. Entrapment of vacancies by impurities with a covalent radius greater than that of Si can lead to a slowdown in the formation of radiation defects. The interaction of isovalent impurities (Sn, Pb, C, Ge), designated D, with A-centers leads to the formation of DVO complexes for the $\text{D} + \text{VO} \rightarrow \text{DVO}$ reaction, the stability of which is higher compared to defects of the VO type. SnVO complexes are significantly more stable than GeVO; Sn does not form bonds with O_i and inhibits the formation of VO centers in irradiated Si. Doping with this impurity could be considered as a way to improve radiation resistance, but, in addition to reducing the efficiency of the formation of A-centers, divacancies and E-centers, the Sn–V complex creates deep energy levels (recombination centers) in the silicon bandgap, i.e., in fact, one type of radiation defect is supplemented by the other two [24]. The peculiarities of the accumulation of radiation defects in n-Si(Sn) fully explain the accelerated degradation of the lifetime of non-equilibrium charge carriers in this material when irradiated [25]. Consequently, the direct use of n-Si(Sn) as a material intended for the manufacture of solid-state electronic products, the use of which is supposed to be in the fields of ionizing radiation, is not possible.

Lead (Pb) in silicon forms clumps of atoms with a size $\approx 10 \mu\text{m}$ [26]. This excludes the use of this material for the production of standard npn structures with a base width $\leq 0.02 \mu\text{m}$ and, most likely, high-voltage npnp structures due to shorting of the active layers. The presence of Pb in silicon does not inhibit the formation of deep acceptors, which include vacancies, from which the authors [27] conclude that

the use of this impurity is ineffective to increase the radiation resistance of Si.

From the point of view of assessing the possibility of practical application of isovalent doping to reduce the concentration of vacancy-oxygen complexes, the calculation of impurity-defect interaction can be carried out using the law of acting masses (mass action analysis) [28]. Defect concentration (is denoted as $[XY]$) with binding energy E_b with respect to the concentration of unbound defects X и Y (i.e. $[X]$ и $[Y]$ respectively) is defined as follows:

$$\frac{[XY]}{[X][Y]} = \exp\left(\frac{-E_b}{k_B T}\right), \quad (1)$$

where k_B is the Boltzmann constant, T is the temperature.

$$E_b = E_{\text{defect cluster}} - \sum E_{\text{isolated defects}}, \quad (2)$$

where E_b is the binding energy of defects in a cluster.

The negative binding energy of defects in a cluster is energetically more advantageous (the energy of defects in a cluster is less than in an isolated state). For the data given in the cited work, a certain pattern can be traced [29]. At the E_b of the DV complex $\cong 0.5$ of this value for the DVO complex, impurity-vacancy complexes are predominantly formed, which are recombination centers (Sn-V, Pb-V). The GeV complex is not formed at 300K, it is possible to form a GeVO complex (instead of the A-center), which makes such complexes effective in terms of increasing the radiation resistance of Si.

2.3. Use of SiGe to Increase the Radiation Resistance of npnp Structures – Previous Results

The thyristor n-p-n-p-structure is a convenient physical model for conducting studies to improve radiation resistance using non-standard impurity-doped Si. Most of the characteristics of a thyristor are determined by the quality of its wide base area ($\sim 150 \mu\text{m}$ with a wafer thickness of $\sim 200 \mu\text{m}$). Research has been carried out on the use of CZ-Si single crystals $\langle \text{P, Ge} \rangle$ in the manufacture of low-power thyristors (reverse applied voltage up to 100 V) [30, 31]. The method of constructing dose dependencies for the mean value of the holding current, leakage current for the sample of irradiated thyristors was applied.

It is shown that for the measured values of the characteristics of discrete low-power devices, high deviations of the numerical values of electrophysical characteristics from their average values are observed, especially for the holding current of devices manufactured on SiGe. Statistical analyses were performed for min and max values of D_T . The most probable values (extremes of distributions) of the thyristor holding currents on Si and Si $\langle \text{Ge} \rangle$ before and

after irradiation are almost the same. Therefore, it is necessary to construct a dose dependence of $I_h(D_T)$ for thyristors manufactured on Si (control) and SiGe (investigated devices) in order to determine the real technological feasibility of using isovalent doping with Germanium to increase radiation resistance. In addition, the physical causes of the high "noise" of the experimental data, i.e. their multidirectional deviation from the mean value, have not been considered before. In the publication [32] it is shown that a change in the concentration of Ge (it can be a deviation in the properties of the raw materials used) has a strong impact on the quality of products and, thus, on their radiation resistance during further operation in the hazard environment. For example, as shown in [33], there is a sharp deterioration in the radiation resistance of npn structures, fabricated on SiGe with $N_{\text{Ge}} = 0.05 \text{ at. \%}$ ($2.5 \cdot 10^{19} \text{ cm}^{-3}$). Therefore, with an accuracy, sufficient for the practical application of SiGe, it can be considered that the concentration of Ge, which is acceptable for the manufacturing of planar diffusion npn structures (it may be assumed that as well as for npnp structures) is approximately equal to 0.1 at. %, or, in other units for reference: $N_{\text{Ge}} \cong 0.2 \text{ mass \%}$; $5 \cdot 10^{19} \text{ cm}^{-3}$. From the technological point of view area $N_{\text{Ge}} < 0.1 \text{ at. \%}$ is unstable, with abrupt changes in yield of suitable products. Use SiGe with a concentration of $N_{\text{Ge}} > 0.2 \text{ at. \%}$ for the manufacture of high voltage npnp structures is not effective.

Thus, the main purpose of this work was to compare the processes of radiation degradation of individual thyristors made on Si and SiGe, and not on a sample of devices made on the control and test material. A special feature of the work is the emphasis on the analysis of the individual properties of the devices in order to assess the physical causes that determine their radiation resistance.

3. Specific Features of SiGe and Control Thyristors Before Irradiation

3.1. Materials and Devices to be Tested, Irradiation

CZ-SiGe single crystals doped with phosphorus with $\rho \approx 35 \Omega \cdot \text{cm}$ were used in the research. In the manufacture of low-power thyristors (inverse applied voltage up to 100 V), single crystals of silicon grown by the Czochralski method (CZ-Si $\langle \text{P, Ge} \rangle$) with a phosphorus concentration $\sim 3 \cdot 10^{14} \text{ cm}^{-3}$, Ge $\sim 5 \cdot 10^{19} \text{ cm}^{-3}$ were used and as well as control single crystals with the same concentration of phosphorus. For the manufacture of thyristors, the standard planar-diffusion technology of 2Y102Г was chosen as the basic technology, Fig. 1.

The appearance and dimensions of the irradiated thyristors is given in Fig. 2.

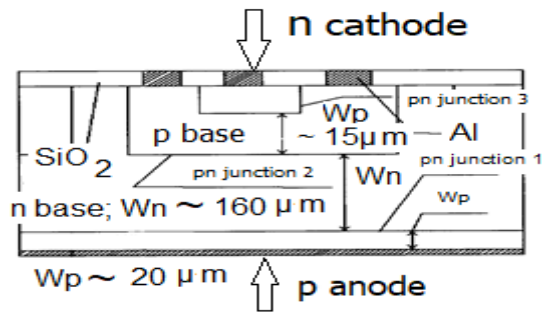


Fig. 1. Vertical structure of the experimental thyristor [34].

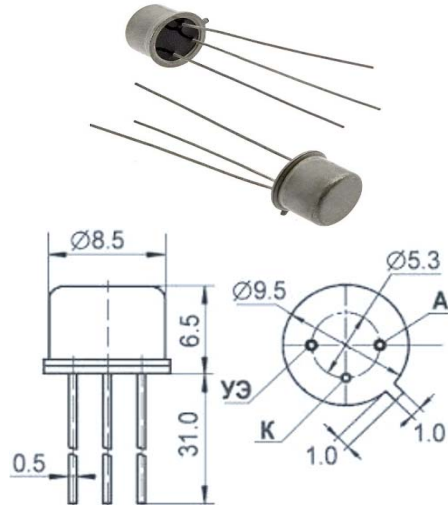


Fig. 2. Appearance and dimensions of the thyristors manufactured with the use of SiGe [35].

3.2. Holding Current (I_h), Leakage Current ($I_{leakage}$) of Control Thyristors and Those Manufactured on SiGe Before Irradiation

The thyristor structure can be switched off, if the voltage between the cathode and the anode decreases to a value at which the anode current becomes less than the so-called "holding current", I_h , which is one of the important parameters characterizing the device structure [36]. Its numerical value determines the possibility of adequate operation of the thyristor in specific applications, especially under irradiation. Measuring the holding current is a fairly simple task, see Fig. 3. I_h and V_h are the coordinates of the holding point beyond which the device is in the on state. In the holding current measurement, the open current is reduced from the set point until the thyristor is switched to the closed state, and the open state current is measured at the time immediately preceding the thyristor enters the closed state.

For the statistical processing of the experimental data, were used Origin PRO, STATISTICA10 and MathCAD15. The results visualization of I_h measurements before irradiation are in the Fig. 4, distribution characteristics are in the Table 2.

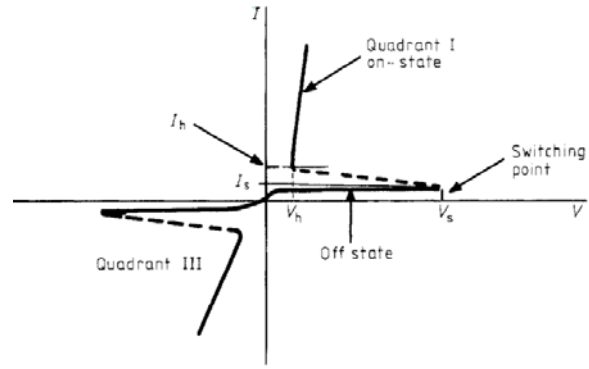


Fig. 3. Volt-ampere characteristic of a thyristor. I_s and V_s , are the coordinates of the variously called switching, turn-on or breakover point.

Table 2. Si and SiGe thyristors holding current (I_h) statistical distribution characteristics.

No.	Characteristic	Control Si	SiGe
1.	Mean value	14.699	14.72
2.	Standard deviation	± 2.02	± 1.422

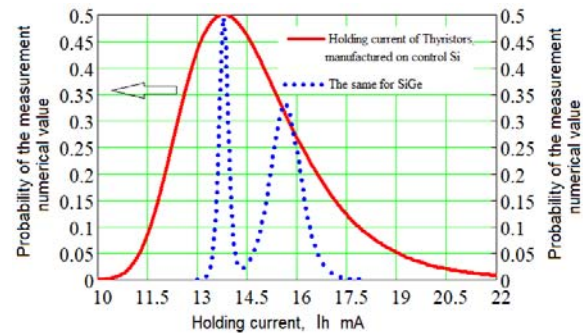


Fig. 4. Probability of the numerical values of holding current (mA) for thyristors fabricated with Si and SiGe.

The leakage currents of the test thyristors are 3 times higher, than those of thyristors, made on isovalently-doped silicon, Fig. 5, Table 3.

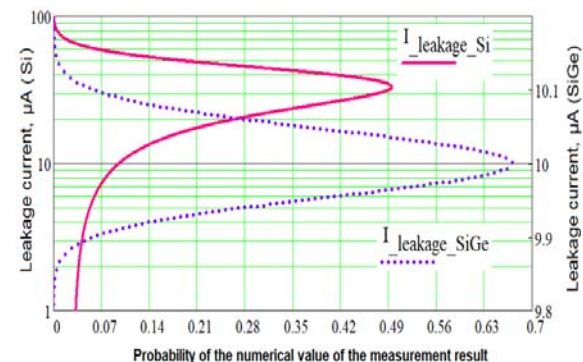


Fig. 5. Probability of numerical values of leakage current (μA) for the thyristors manufactured with Si and SiGe.

Table 3. Si and SiGe thyristors leakage current (I_{leakage}) statistical distribution characteristics.

No.	Characteristic	Control Si	SiGe
1.	Mean value	32.896	10.0
2.	Standard deviation	± 13.031	± 0.045

Thyristors manufactured with SiGe are of higher quality from the very beginning, prior to irradiation, which suggests their higher radiation resistance to γ -exposure.

4. Doping of Si by Germanium: Experience of Use to Increase npnp – Structures Radiation Resistance

4.1. Effect of γ -irradiation on the Holding Current (I_h) of Low-power Control Thyristors

The presence of pronounced distributions (including bimodal distributions) of the physical characteristics of npnp structures indicates the possibility of an individual response of each sampling device to external influences, including the action of ionizing radiation [37].

This phenomenon is due to the spread of properties of raw materials and materials, the instability of the modes of technological operations etc. All real semiconductor devices are in quasi-stationary states, the levels of stability of which may differ from each other. Therefore, the already complex internal state of Si abruptly changes under the influence of external excitations, i.e., destabilizing factors, especially ionizing irradiation. Under the influence of these factors, in the case of inevitable statistical variations in the properties of raw materials and random deviations of the modes of technological operations, each of semiconductor devices has an individually specific internal state at each moment of time, which determines its technical characteristics, as existing, as well as future in hazard environment.

The specific individual characteristics of each of the thyristors provide the individual way of degradation of their physical properties, when irradiated. For example, experimental results for the X5 thyristor (dependence $I_h(D_\gamma)$) in MathCAD can be approximated as follows, Fig. 6.

For $D_\gamma \leq 10^3$ mSv Extreme model was used, for higher doses – FreundlichEXT [38].

So, individual way of degradation of the thyristors physical properties, when irradiated, was confirmed experimentally. The individual characteristics of each of the thyristors vary in the wide range, Figs. 7, 8 and other drawings.

The process of the devices X5, X6 radiation degradation may be explained as follows. A decrease in I_h can be observed with an increase in lifetime value

of the minority charge carriers, τ_p , in the wide n-base of control thyristors, in accordance with well-known formula [39]. It approximately (qualitatively) expressing the dependence of the holding (switching off) current of the thyristor, taking into the consideration its geometric dimensions and electrical characteristics of the material, on which the device was manufactured:

$$I_h \sim \frac{W_n}{\tau_p \cdot \mu_p \cdot \rho_n \cdot \ln\left(\frac{1}{1-\alpha_2}\right)}, \quad (3)$$

where W_n is the thickness of the thyristor n- base; τ_p , μ_p is the lifetime and mobility of minor charge carriers in the n-base of the thyristor, respectively; ρ_n is the resistivity of the thyristor n-base material; α_2 is the current transfer coefficient of a thyristor n-p-n fragment with a narrow p-base.

Experimental results

60	19.2
120	18
360	16
1440	18.5
2880	18
7800	18
42120	17.9
60480	18.9
259200	19.7
2938000	15

$I_{\text{hold_X5_D_}\gamma_ \text{experim}} :=$

γ -irradiation dose, mSv,
holding, mA

$D_\gamma \text{ X5 experim} := I_{\text{hold_X5_D_}\gamma_ \text{experim}}^{(0)}$
 $I_{\text{hold_X5_experim}} := I_{\text{hold_X5_D_}\gamma_ \text{experim}}^{(1)}$

Low dose approximation ($D_\gamma \approx 10 \dots 3 \cdot 10^3$ mSv)

$y0_I_{\text{hold_X5_low_dose}} := 19.2$ $xc_I_{\text{hold_X5_low_dose}} := 360$

$w_I_{\text{hold_X5_low_dose}} := 370.944$ $A_I_{\text{hold_X5_low_dose}} := -3.2$

$z_I_{\text{hold_X5_low_dose}}(D_\gamma) := \frac{1}{0.65} \cdot \frac{(D_\gamma - xc_I_{\text{hold_X5_low_dose}})}{w_I_{\text{hold_X5_low_dose}}}$

$I_{\text{hold_X5_low_dose}}(D_\gamma) :=$

$y0_I_{\text{hold_X5_low_dose}} + \dots$

$\dots + A_I_{\text{hold_X5_low_dose}} \cdot \exp(-\exp(-z_I_{\text{hold_X5_low_dose}}(D_\gamma))) - \dots$

$\dots - z_I_{\text{hold_X5_low_dose}}(D_\gamma) + 1)$

High dose approximation

$a_X5 := 27.75166$ $b_X5 := -0.17484$ $c_X5 := 0.14081$

$I_{\text{hold_X5}}(D_\gamma) := a_X5 \cdot D_\gamma^{b_X5} \cdot \exp(-c_X5 \cdot D_\gamma)$

$I_{\text{hold_general_X5}}(D_\gamma) := \begin{cases} I_{\text{hold_X5_low_dose}}(D_\gamma) & \text{if } 1 \leq D_\gamma \leq 0.73 \cdot 10^3 \\ I_{\text{hold_X5}}(D_\gamma) + 0.1 & \text{if } 7 \cdot 10^2 \leq D_\gamma \leq 1 \cdot 10^7 \end{cases}$

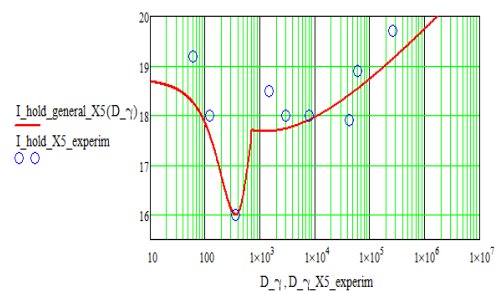


Fig. 6. Holding current calculation in MathCAD. Example: control thyristor X5, manufactured on Si.

Probable cause of the τ_p change there may be a so-called "low-dose effect" of radiation exposure [40]. The action of irradiation of γ -rays on defect-containing semiconductor crystals, with a dose less than 10^3 J/kg does not lead to additional accumulation of defects but conversely leads to elimination of defects and transition of the crystal to a more equilibrium state. Ionization processes rearrange defects in crystals. It occurs as a result of liberation of stored energy in the crystal due to the chain reactions of annihilation of defects, initiated by ionization. Transition of the crystal to the equilibrium state is accompanied by improvement of its physical properties, τ_p , first of all. This provides a significant improvement (sharp peaks) in the radiation resistance of the X5 and X6 devices – reduction in their holding currents.

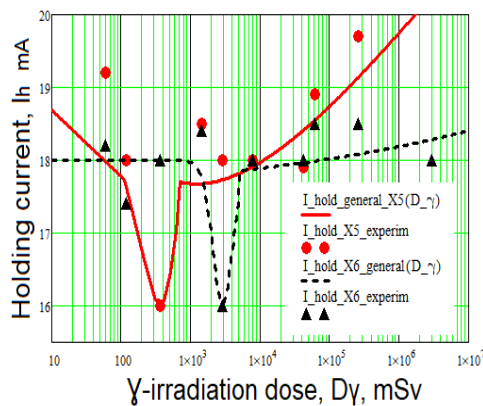


Fig. 7. Degradation of the holding current of thyristors X5 and X6, manufactured on the control Si (in all figures: solid, dashed or point lines – models; symbols – experimental data)

Degradation of the second group of the control thyristors (1X and X1_zv) in the range $D_\gamma \approx 1 \cdot 10^2 \dots 1 \cdot 10^4$ mSv (zone of the transition processes) shown on Fig. 8. There is an obvious deterioration in the properties of the control thyristors, which is expressed in the appearance of one or two extremes of I_h , the occurrence of which, apparently, can also be explained by the application of the formula (), i.e., by a decrease in τ_p , μ_p in the thyristors wide n-base. For these devices (the second group of thyristors) in the transient D_γ zone, there is a decrease in the individual radiation resistance of the control thyristors, and, obviously, their parametric failure (unauthorized switching of the thyristors to a closed state) is possible when irradiated.

The transient area associated with the "low dose" effect may be smoothed out, Fig. 9.

Unstable radiative change in thyristor holding current X2 at $D_\gamma \approx 1 \cdot 10^2 \dots 1 \cdot 10^4$ mSv resembling an oscillatory process, resulting in high stability of $I_h(D_\gamma)$ при $D_\gamma \approx 1 \cdot 10^4 \dots 3 \cdot 10^6$ mSv (Fig. 10).

For $D_\gamma \geq 10^4$ mSv for control thyristors, there is a monotonic relationship $I_h(D_\gamma)$, which is individual for each device, too.

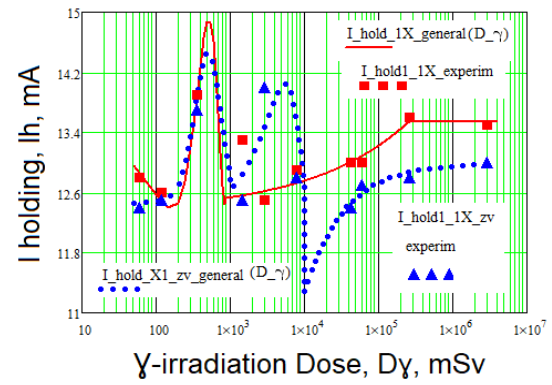


Fig. 8. Degradation of the holding current of thyristors 1X and X1_zv, manufactured on the control Si.

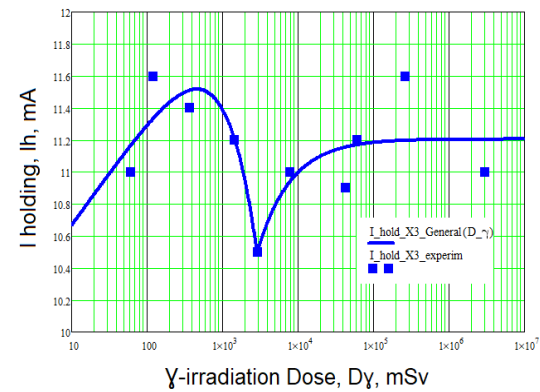


Fig. 9. Holding current radiation degradation of the thyristor X3, manufactured on the control Si.

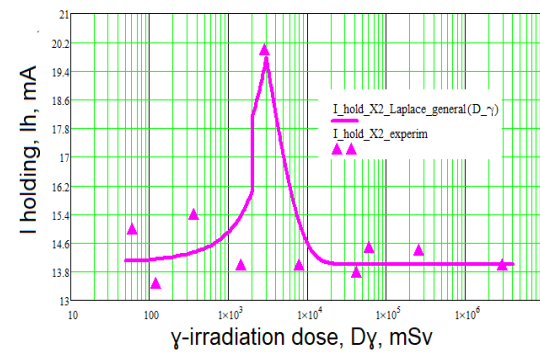


Fig. 10. Dependency modeling $I_h(D_\gamma)$ of the thyristor X2.

4.2. Effect of γ -Irradiation on the Holding Current (I_h) of Low-power Thyristors, Manufactured on SiGe

Doping of Si by Ge sufficiently changes nature of the radiation degradation of the thyristors, Figs. 11-13.

For some devices (e.g. G5) the shape of the $I_h(D_\gamma)$, which suggests the presence of two regions of D_γ in which the thyristor holding current changes due to processes resembling the "low-dose effect", namely – $D_\gamma \approx 2 \cdot 10^1 \dots 1 \cdot 10^3$ mSv and $D_\gamma \approx 5 \cdot 10^4 \dots 3 \cdot 10^6$ mSv.

This correlates with availability of bimodal distribution of SiGe thyristors I_h before γ -irradiation. Dependency of $I_h(D_\gamma)$ for the other devices (Fig. 12, Fig. 13) is less complicated, but not repetitive.

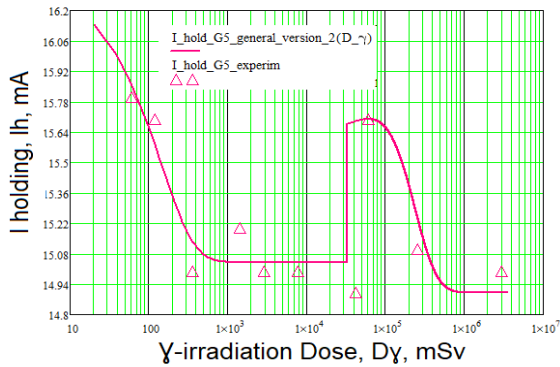


Fig. 11. Degradation of the holding current of a G5 thyristor, manufactured on SiGe.

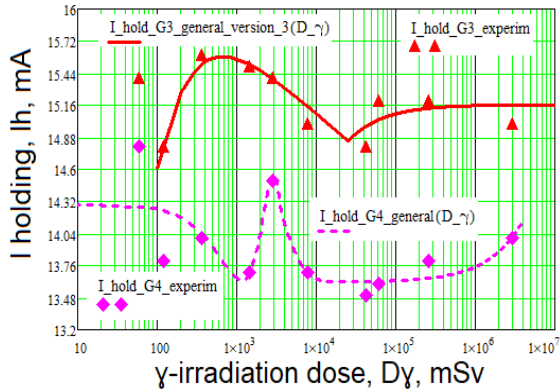


Fig. 12. Degradation of the holding current of G3 and G4 thyristors, manufactured on SiGe.

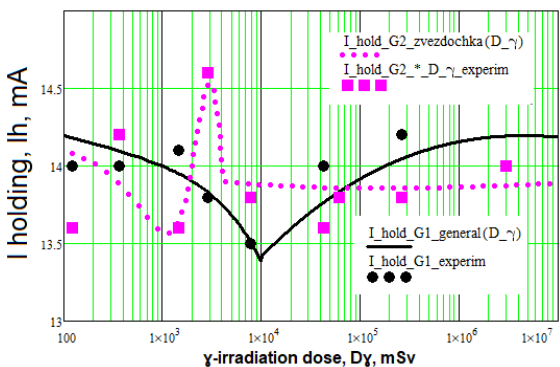


Fig. 13. Degradation of the thyristors holding current G1 and G2_zvezdochka (or *), manufactured on SiGe.

Is it possible to use SiGe to increase the radiation resistance of discrete low-power thyristors? For the illustrative answer, it is necessary to compare the average values of $I_h(D_\gamma)$ in accordance with (4) for the thyristors, manufactured with Si and SiGe.

$$I_{hold_average}(D_\gamma) = \frac{1}{n} \cdot \sum_i^n I_{hold_i}(D_\gamma), \quad (4)$$

where $I_{hold_i}(D_\gamma)$ is the holding current of the i -th thyristor; n is the number of the thyristors to be averaged.

Results of calculations are shown in Fig. 14.

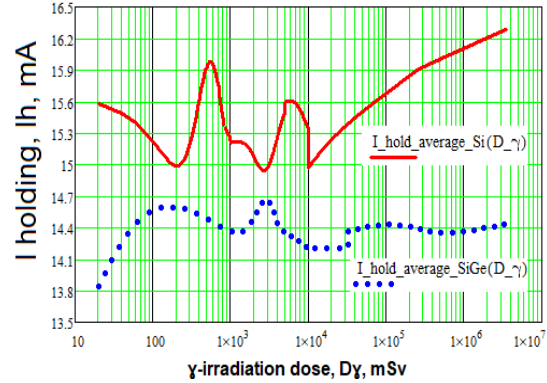


Fig. 14. Comparison of changes in $I_{hold_average}(D_\gamma)$ in the dose range of γ -irradiation for the thyristors, manufactured on Si and SiGe.

The radiation resistance of the control Si thyristors decrease significantly at $D_\gamma \approx 1 \cdot 10^4 \dots 3 \cdot 10^6$ mSv – $I_h(D_\gamma)$ increases markedly both in absolute units, mA, (Fig. 14), and in relative terms, Fig. 15.

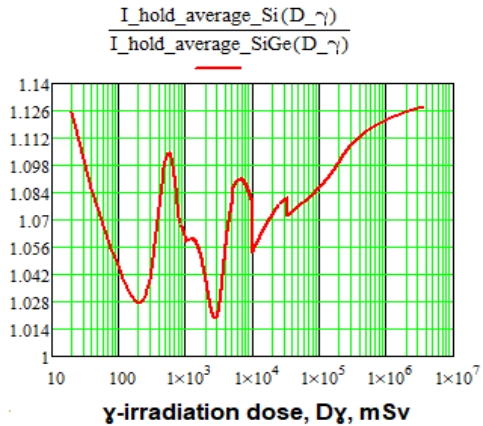


Fig. 15. Ratio of average holding current ($I_{hold_average_Si}(D_\gamma)$) of the thyristors X5,X6,IX,X1zv, (Si) to the same characteristic ($I_{hold_average_SiGe}(D_\gamma)$) of the G1,G4,G5,G3 (SiGe).

For $D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^2$ mSv there is a decrease in $I_h(D_\gamma)$. Most likely, this is the area of manifestation of the "low-dose effect" of γ -irradiation for control devices (slight growth τ_p in the n-base of the thyristors, manufactured on Si). For SiGe devices, there is an increase in the holding current, therefore, the "low dose effect" is not manifested. Range $D_\gamma \approx 1 \cdot 10^2 \dots 1 \cdot 10^4$ mSv can be considered as an area of unstable operation of the control thyristors in the

radiation field. Perhaps it is more accurate to call it the "degradation noise area" $I_h(D_\gamma)$. For the control devices (Si), the amplitude of the oscillations reaches 0.9 mA, and for the thyristors on SiGe 0.3 mA. Fluctuations are "smoothed out" by about three times. For $D_\gamma \geq 1 \cdot 10^4$ mSv there is an expected increase in $I_h(D_\gamma)$ for thyristors, fabricated in Si (Fig. 16). Devices made with SiGe are sufficiently more stable.

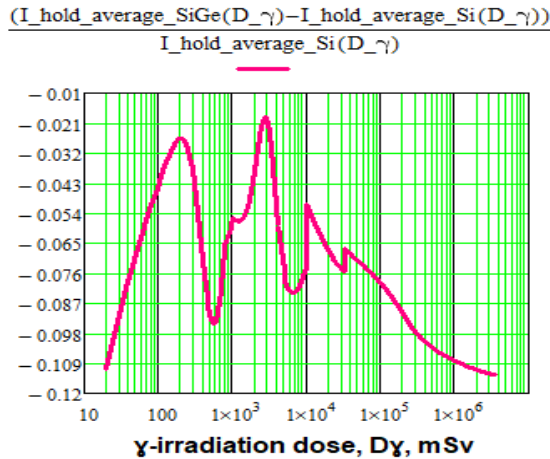


Fig. 16. Relative decrease in $I_h(D_\gamma)$ of the thyristors, manufactured on SiGe, compared to control devices under γ -irradiation.

The effect of isovalent doping on radiation resistance was calculated in MathCAD using the interval average value, Figs. 17, 18. The holding current ratio is the degree of increase in the radiation resistance of thyristors manufactured with SiGe compared to control devices (the *higher* the $I_{hold_average}$ at a given radiation dose, the *lower* is the radiation resistance of the thyristor).

$D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^4$ mSv ("low-dose effect", area of unstable operation of the control thyristors in the radiation field):

$$\frac{1}{1 \cdot 10^4 - 10} \int_{10}^{1 \cdot 10^4} I_{hold_average_Si}(D_\gamma) dD_\gamma = 15.372$$

$$\frac{1}{1 \cdot 10^4 - 10} \int_{10}^{1 \cdot 10^4} I_{hold_average_SiGe}(D_\gamma) dD_\gamma = 14.378$$

Improvement of the radiation hardness for the SiGe thyristors $\frac{15.372}{14.378} = 1.069$

Fig. 17. Calculation in MathCAD of average interval averages of holding currents, $I_{hold_average}$, for control thyristors manufactured on Si and devices manufactured on SiGe: *low doses*.

Therefore, for $D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^4$ mSv the use of SiGe makes it possible to increase the average interval radiation resistance of thyristors by approximately

7 %, and in the range of $D_\gamma \approx 1 \cdot 10^4 \dots 1 \cdot 10^6$ mSv $\approx$ up to 12 %.

$D_\gamma \approx 1 \cdot 10^4 \dots 3 \cdot 10^6$ mSv (operation of the thyristors under high dose conditions of γ -irradiation):

$$\frac{1}{3 \cdot 10^6 - 10^4} \int_{10^4}^{3 \cdot 10^6} I_{hold_average_Si}(D_\gamma) dD_\gamma = 16.115$$

$$\frac{1}{3 \cdot 10^6 - 10^4} \int_{10^4}^{3 \cdot 10^6} I_{hold_average_SiGe}(D_\gamma) dD_\gamma = 14.388$$

Improvement of the radiation hardness for the SiGe thyristors $\frac{16.115}{14.388} = 1.12$

Fig. 18. Calculation in MathCAD of average interval averages of holding currents, $I_{hold_average}$, for Si control thyristors and SiGe devices: *high doses*

The greater the nonlinearity of the processes that take place in a discrete device at certain values of D_γ , the more difficult it is to increase its radiation resistance using isovalent doping by Ge.

At the same time, ensuring radiation resistance for a sample of devices does not exclude failures of individual thyristors. For individual control devices in the range $D_\gamma \approx 1 \cdot 10^5 \dots 3 \cdot 10^6$ mSv (experimental points $I_{hold_X5_experim}$, $I_{hold_X6_experim}$) there is a significant decrease in radiation resistance, which is understood as an increase in the I_h , compared to other control thyristors, up to ≈ 19 mA (Fig. 19).

For example, mean value of the holding current $I_h \approx 13.125$ mA for thyristors $I_{hold1_1X_experim}$, $I_{hold1_1X_zvezdochka_experim}$, i.e. about 44.8 % lower. A similar significant increase I_h by 29.7 % for the thyristors X5, X6 is observed when compared to thyristors manufactured on SiGe ($I_{hold_G1_experim}$, $I_{hold_G1_experim}$, medium $I_h \approx 14.7$ mA).

The absence of observed abrupt increases in I_h ("ejections") for devices, manufactured on SiGe, can partly be considered as an increase in their radiation resistance in comparison with control thyristors.

4.3. Effect of γ -irradiation on the Leakage Current ($I_{leakage}$) of Low-power Control Thyristors

The special feature of the leakage current ($I_{leakage}$) of the control devices is the presence of two extremes (Fig. 20), located in the range $D_\gamma \approx 10^2 \dots 10^4$ mSv.

Extremum location is closely related to the location of the I_h peaks. This makes it possible to assume that leakage currents reach *max* at D_γ , corresponding to the *min* lifetime value of the minority charge carriers τ_p in the n-base of control thyristors, in which I_h tends to the *max* value, Fig. 21.

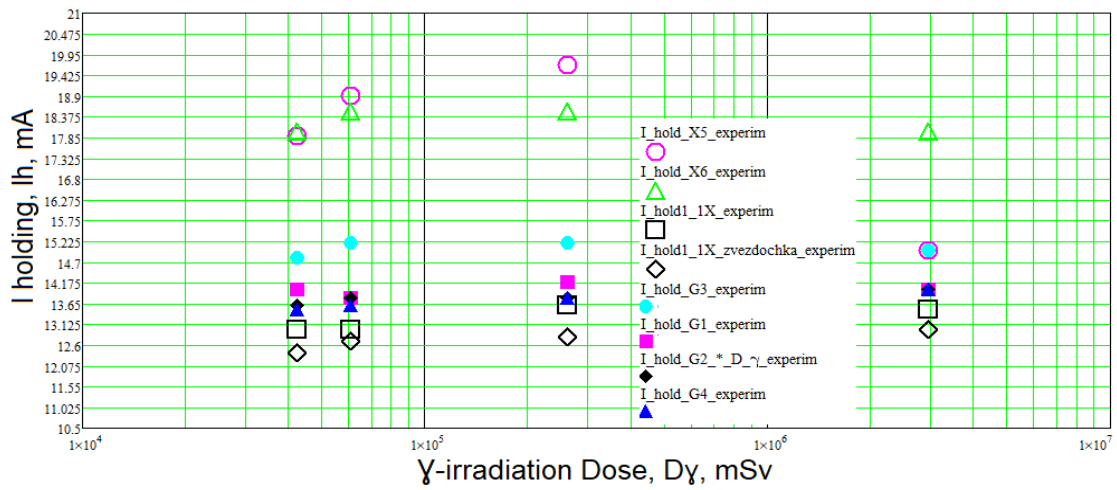


Fig. 19. Comparison of experimental results for selected Si and SiGe thyristors in the high dose range.

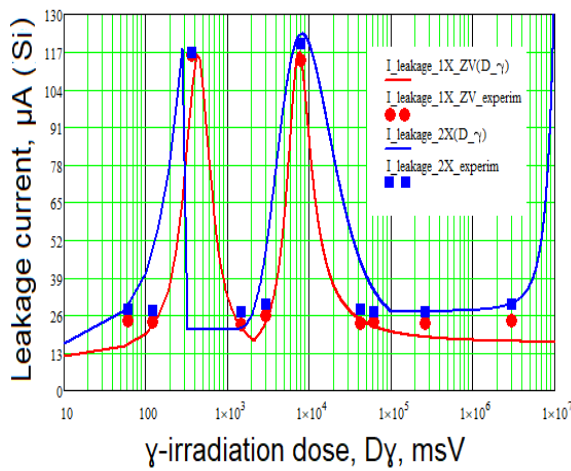


Fig. 20. Bimodal dose dependence of leakage currents of the control thyristors 1X_ZV, 2X.

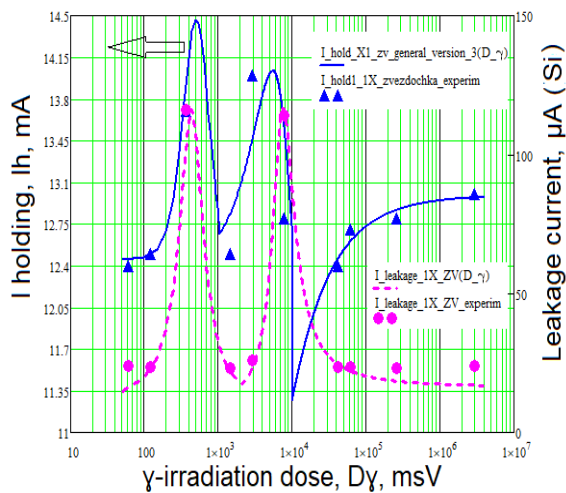


Fig. 21. Correlation between holding current and leakage current on the example of the control thyristor "1X with an Asterisk".

4.4. Effect of γ -irradiation on the Leakage Current ($I_{leakage}$) of Low-power Thyristors, Manufactured on SiGe

Nonlinear dependence between holding current and leakage current for the thyristors, manufactured on SiGe, also exists, but expressed differently, then for control devices, Fig. 22.

At $D_\gamma < 10^4$ mSv leakage current lags slightly behind holding current, and at $D_\gamma > 10^4$ mSv it is significantly ahead of it.

From the practical point of view (increasing the radiation resistance of the thyristor according to the criterion of a significant reduction in the leakage current), the device 1G, manufactured on SiGe, is of interest, Fig. 23.

The BiHill model, approximates the dependency, Fig. 24. Results of the calculations are shown in the Fig. 25.

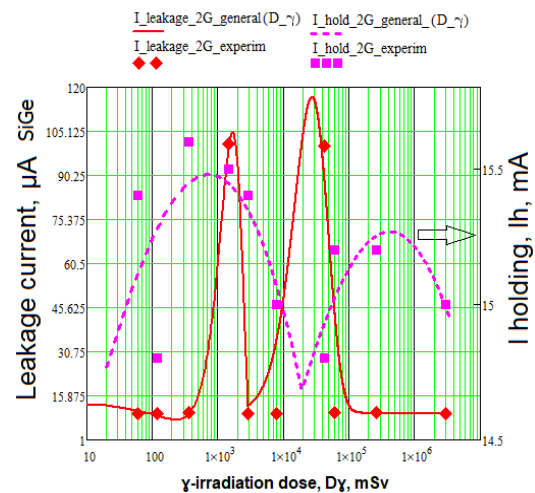


Fig. 22. Correlation between holding current and leakage current on the example of the SiGe thyristor "2G".

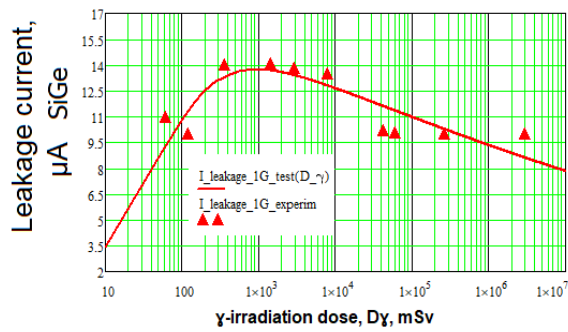


Fig. 23. Dependence of leakage current on D_γ the example of the SiGe thyristor "1G".

$$I_{\text{leakage_1G_D_}\gamma\text{_experim}} := \begin{pmatrix} 60 & 11 \\ 120 & 10 \\ 360 & 14 \\ 1440 & 14.1 \\ 2880 & 13.8 \\ 7800 & 13.5 \\ 42120 & 10.2 \\ 60480 & 10.1 \\ 259200 & 10 \\ 2938000 & 10 \end{pmatrix}$$

$$D_{\gamma_1G_experim} := I_{\text{leakage_1G_D_}\gamma\text{_experim}}^{<0>}$$

$$I_{\text{leakage_1G_experim}} := I_{\text{leakage_1G_D_}\gamma\text{_experim}}^{<1>}$$

$$Pm_I_{\text{leakage_1G}} := 29.40982 \quad 691.02483$$

$$Ka_I_{\text{leakage_1G}} := 47.5714 \quad 408.35908$$

$$Ki_I_{\text{leakage_1G}} := 795.93659 \quad 336100.2427$$

$$Ha := 0.93261 \quad 1.75983$$

$$Hi := 0.1074 \quad 1.03946$$

$$I_{\text{leakage_1G_test}}(D_\gamma) := \frac{Pm_I_{\text{leakage_1G}}}{\left[1 + \left(\frac{Ka_I_{\text{leakage_1G}}}{D_\gamma}\right)^{Ha}\right] \cdot \left[1 + \left(\frac{D_\gamma}{Ki_I_{\text{leakage_1G}}}\right)^{Hi}\right]}$$

Fig. 24. Calculation in MathCAD of leakage current, for 1G thyristors manufactured on SiGe.

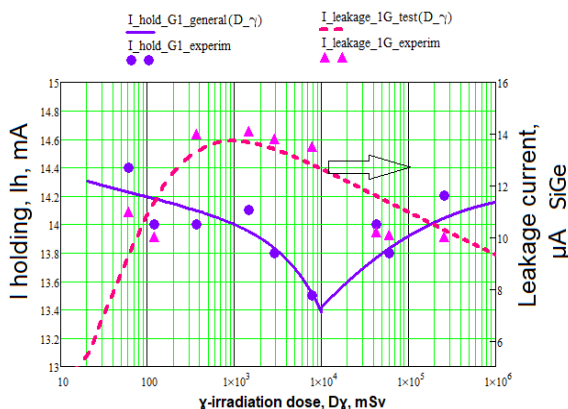


Fig. 25. Calculation in MathCAD of the leakage current for the 1G thyristor, manufactured on SiGe.

7. Conclusions

1. Radiation degradation during γ -irradiation of discrete low-power thyristors, both control (Si) and SiGe-fabricated, is a complex nonlinear process that is individual for each device.

2. It is possible to distinguish three γ -irradiation ranges, in which the degradation of the average holding current for control and investigated thyristors proceeds in different ways, namely:

2.1. For $D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^2$ mSv there is a decrease in $I_h(D_\gamma)$ for control Si devices. It may be manifestation of the "low-dose effect" of γ -irradiation thyristors, manufactured on Si. For SiGe devices, there is an increase in the holding current, therefore, the "low dose effect" is not manifested.

2.2. Range $D_\gamma \approx 1 \cdot 10^2 \dots 1 \cdot 10^4$ mSv can be considered as an area of unstable operation of the control thyristors in the radiation field. Perhaps it is more accurate to call it the "degradation noise area" of $I_h(D_\gamma)$. Devices made with SiGe are sufficiently more stable.

2.3. For $D_\gamma \geq 1 \cdot 10^4$ mSv there is an expected increase in $I_h(D_\gamma)$ for thyristors, fabricated in Si. SiGe devices continue to be more stable. Thus, from a qualitative point of view, the use of isovalent doping with germanium increases the radiation resistance of low-power thyristors

3. For $D_\gamma \approx 1 \cdot 10^1 \dots 1 \cdot 10^4$ mSv use of SiGe makes it possible to increase the average interval radiation resistance of thyristors by approximately 7 %, and in the range of $D_\gamma \approx 1 \cdot 10^4 \dots 1 \cdot 10^6$ mSv $\approx$ up to 12 %.

4. The greater the nonlinearity of the processes that take place in a discrete device at certain values of D_γ , the more difficult it is to increase its radiation resistance using isovalent doping by Ge (low and high doses for $I_h(D_\gamma)$). At the same time, ensuring radiation resistance for a sample of devices does not exclude failures of individual thyristors.

5. The leakage current (I_{leakage}) and holding current (I_h) of the control Si thyristor are more correlated, than for the SiGe thyristors. The model of the process has to be considered.

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Enhancing Traffic Management through Visible Light Communication-Driven Signaling and Cooperative Trajectories

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Abstract: Visible Light Communication (VLC) is a promising solution proposed for optimizing traffic signals and vehicle trajectories at urban intersections. This approach utilizes light communication between connected vehicles (CVs) and infrastructure to enable coordinated traffic interactions. By leveraging streetlamps, intersection signals, and headlights, VLC facilitates the transmission of information between CVs and the infrastructure. The system is designed to be flexible and adaptive, accommodating diverse traffic movements across multiple signal phases. To evaluate the effectiveness of VLC, simulations are conducted using the SUMO urban mobility simulator. These simulations generate traffic flows and incorporate VLC mechanisms and relative pose concepts for queueing, requesting, and responding to interactions. To dynamically control traffic flows and alleviate congestion during peak hours, a deep reinforcement learning algorithm is employed. This algorithm optimizes traffic by utilizing both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Comparisons are made between the traditional trajectory and signal optimization techniques. The results demonstrate the benefits of VLC in terms of throughput, delay, and the reduction of vehicle stops. In conclusion, VLC presents an integrated approach that harnesses light communication to optimize traffic signals and vehicle trajectories at urban intersections. Through simulations and comparisons, VLC proves its effectiveness in enhancing traffic efficiency and reducing congestion, offering promising insights for future urban traffic management systems.

Keywords: Visible light communication, Optical sensors, Cooperative traffic control, Connected vehicles, Deep Reinforcement learning; SUMO simulation.

1. Introduction

In today's world, communication technology has become a subject of controversy due to the increasing overload of radio frequencies and the need for stable

and consistent systems. As a potential solution to this challenge, Visible Light Communication (VLC) emerges by utilizing light-emitting diodes (LEDs) as light sources and photodiodes as photodetectors. By modulating visible light in time and frequency, VLC

offers a promising alternative for communication technology [1]. Only light emitting diodes (LED) lamps can be used for the transmission of visible light [2]. This functionality has given rise to a novel communication technology, VLC, where LED luminaires can be used for high-speed data transfer [3]. VLC is an emerging technology [4] that enables data communication by modulating information on the intensity of the light emitted by LEDs. Increasingly, smart cities can become comfortable, quick, and safe places to travel. Technology has advanced to the point where even non-autonomous vehicles are equipped with sophisticated sensors and computers. That was the first step on the road to improve road safety.

The application of VLC goes beyond traditional communication methods and extends to intelligent traffic control systems. By implementing a real-time traffic control system, traffic flow can be significantly improved through effective resource management and information exchange. This study specifically focuses on utilizing Visible Light Communication as a means of transmitting information, providing guidance services, and delivering specific information to drivers. In the case of vehicular communications, the use of VLC is made easier because all vehicles, streetlights, and traffic lights are equipped with LEDs, using them for illumination. In this context, communication and localization are facilitated through the utilization of streetlamps, traffic signaling, and the headlights and taillights of vehicles. This approach allows for the simultaneous use of outdoor automotive lighting and infrastructure lighting to serve both illumination and communication purposes [5, 6].

We propose a cooperative I2V2V2I2V system that supports guidance services. This system employs an edge/fog-based architecture, which effectively manages the safe passage of vehicles through connected intersections. Vehicular Communication Systems are a type of network in which vehicles and roadside units are the communicating nodes, providing each other with information [7]. The main objective is to optimize traffic safety and efficiency on public roads through V2V and V2I communications [8-10]. Real-time traffic information is essential for optimizing traffic light duration. By monitoring the location, speed, and direction of nearby vehicles, significant improvements in traffic management can be achieved.

2. Connected Vehicles and VLC

The central aim is to enhance both safety and efficiency on public roads through the implementation of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. This endeavor revolves around elevating situational awareness and curtailing traffic accidents. A key strategy involves utilizing real-time traffic information to inform dynamic adjustments in traffic light durations, ultimately optimizing traffic flow and minimizing potential hazards.

At the heart of this effort lies the integration of V2V and V2I communications. By harnessing the real-time data regarding the location, speed, and direction of nearby vehicles, a comprehensive and accurate understanding of the road environment is achieved. This real-time awareness enables informed decision-making, leading to substantial enhancements in traffic management. The envisioned outcome is a marked improvement in both the safety and efficiency of road usage, offering a promising path towards a smarter and more secure transportation landscape.

2.1. Intelligent Control System

To develop the intelligent control system model that facilitates safe vehicle management through intersections using V2V, V2I, and I2V communications, Reinforcement Learning (RL) concepts were used. RL is a training method based on rewarding desired behaviors and/or punishing undesired ones [11-13].

The simulations were agent-based and they have been carried out in a tool for Simulation of Urban MObility (SUMO) [14].

Fig. 1 illustrates the reinforcement learning loop, where the agent receives the current state of the environment (S_t) and learns from the feedback of the action taken (A_t) on the overall traffic flow. The agent's action directly affects the traffic light, which serves as the controller of the intersection. This iterative process allows the agent to learn from its actions and improve over time, avoiding negative situations and focusing on positive outcomes. The agent's experiences and actions are stored to train a model and enhance its decision-making capabilities [15]. The traffic lights in SUMO are controlled by the learning agent following its decisions, the overall flow of traffic is described, and the actions of the traffic lights control agent are rewarded. The reward (R_t), represent the accumulated total waiting time of all the cars in the intersection captured respectively at agentsteps $t - 1$ and t . The objective of the IM is to minimize the total waiting time at each arm of the intersection. When a vehicle's speed drops below 0.1 m/s, a queue alert is triggered. The IM agent must explore new states while simultaneously maximizing its overall reward. To illustrate this concept, a dynamic phasing diagram and a state matrix based on the total accumulated time are provided.

2.2. Scenario, Environment and Architecture

In Fig. 2a, a scenario with two traffic signal-controlled intersections is depicted. In Fig. 2b illustration of the coverage map in the unit cell, footprint regions (#1-#9) and steering angle codes (2-9) are exemplified.

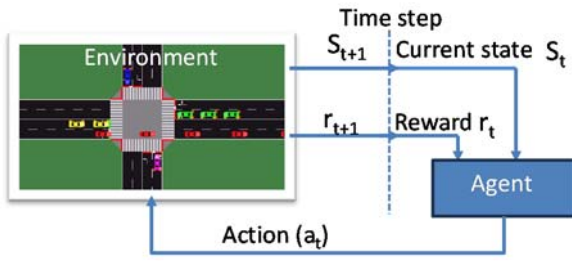


Fig. 1. Illustration of the reinforcement learning's loop of action-reward feedback.

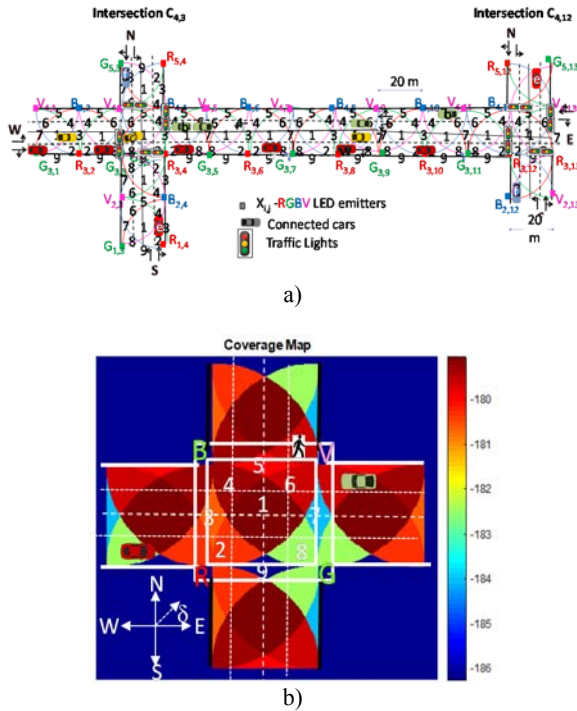


Fig. 2. a) Simulated scenario with the optical infrastructure. b) Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

The environment is defined by a cluster of square unit cells arranged in an orthogonal geometry (Fig. 2a). Different data channels are provided by tetra-chromatic white light (WLEDs) sources positioned at the corners of the square unit cells (Fig. 2b) distributed along the road and at the crossroads. Tetra-chromatic white light (WLEDs) sources, framed at the corners of a square unit cell, provide different data channels. They consist of red, green, blue and violet chips and combine the lights in correct proportion to generate white light. At each node, only one chip of the LED is modulated for data transmission, the Red (R: 626 nm), the Green (G: 530 nm), the Blue (B: 470 nm) or the Violet (V: 390 nm). Modulation and digital-to-analog conversion of the information bits is done using signal processing techniques. The coverage map in a four-legged intersection is displayed in Fig. 2b. The coded nine possible overlaps (#1-#9), defined as fingerprint regions, as well as the possible receiver directions

(Cardinal points; δ) are also pointed out for the intersection.

This layout helps define the structure and arrangement of the intersections within the scenario. Each transmitter, X_{ij} , carries its own color, X , (Red, Green, Blue, Violet) as well as its horizontal and vertical ID position within the surrounding network (ij) [16]. In the Proof of Concept (PoC), it was assumed that the crossroads are situated at the intersections of line 4 with column 3 and column 11.

In Fig. 2, there are two traffic signal-controlled intersections with four traffic flows. From the West, there are twenty red a_i vehicles with straight movement and four yellow c_i vehicles with left turn only. From the East, there are green b_i vehicles with left turn only (thirteen straight and two left turn). From the South, there are six orange e_i vehicles, with two having a left-turn approach and four with straight movement. From the North direction, there are thirteen blue f_i vehicles, with nine going straight and four having a left turn at both intersections. The road request and response segments offer a binary choice between turning left/straight or turning right. The vehicles represent a percentage of the traffic flow, and their ordering in terms of priority is determined. The top three requests are a_1 , b_1 , and a_2 , followed by b_2 , a_3 , and c_1 . In the seventh, eighth, and ninth places are b_3 , e_1 , and a_4 , respectively, followed by c_2 in the tenth place. The penultimate request is a_5 , and the last one is f_1 . Based on the assumptions, there are 540 cars approaching the intersection per hour, with 80 % of them coming from the east and west directions. Among these cars, it is assumed that 50 % of them will make a left or right turn at the intersection, while the remaining 50 % will continue straight.

2.3. Visible Light Communication Link

A Vehicular Visible Light Communication system (V-VLC) is structured around a transmitter and a receiver connected via a wireless channel. The transmitter's role involves generating modulated light, often utilizing the ON-OFF-keying (OOK) amplitude modulation technique. Concurrently, the receiver detects fluctuations in the received light signal [17]. This dynamic system finds implementation in the road infrastructure, manifesting as streetlights, and within the vehicles themselves, taking shape as headlights.

Within this ecosystem, the environment is meticulously defined, characterized by a cluster of square unit cells arranged in an orthogonal configuration. The cornerstone of this setup is the deployment of tetra-chromatic white light sources (WLEDs) positioned strategically at the corners of each unit cell. These light sources offer distinct data channels [18].

Functionally, the V-VLC system processes coded signals as inputs. These signals are transmitted by transmitters, which can take the form of streetlights or headlights. Their purpose ranges from vehicle identification (I2V), communication with traffic lights

(V2I), to facilitating communication between vehicles (V2V). The encoded signals encapsulate not only the essential information about the transmitter's position within the network but also the steering angle (δ) imperative for guiding the driver's orientation along their trajectory.

To manage the seamless passage of vehicles through intersections, a sophisticated interplay of queue/request/response mechanisms and temporal/space-relative pose concepts are employed [19]. These mechanisms ensure efficient traffic management and orderly vehicular movement at crossroads.

The coded signals transmitted by the transmitters are subsequently received and decoded by a PIN-PIN photodetector. This photodetector boasts light filtering properties, ensuring the precision and accuracy of data reception, a pivotal aspect in maintaining the integrity of the communication process.

2.4. Architecture

Illustrated in Fig. 3 is the implementation of a hybrid structure seamlessly fusing mesh networking with cellular technology. At the crux of this configuration is the "mesh" controller, strategically positioned at streetlight installations. This controller assumes the critical role of a message-forwarding entity, orchestrating the efficient flow of information among vehicles operating within the mesh network. Its functionality closely resembles that of router nodes within a network framework.

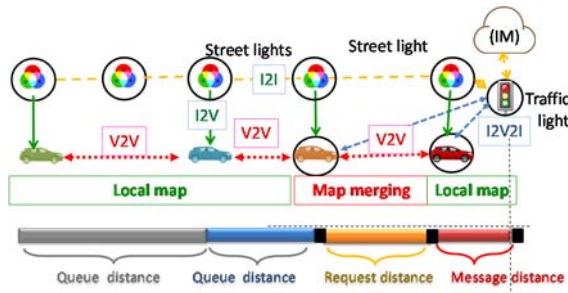


Fig. 3. VLC Edge Computing infrastructure.

Complementing the mesh controller is the hybrid controller, an innovative convergence of mesh and cellular capabilities. This hybrid entity performs a dual role: firstly, it functions as a border-router, skillfully bridging the mesh and cellular domains. Additionally, this hybrid controller serves as a catalyst for edge computing functionalities, effectively extending the computational capacity of the network [20].

This architectural paradigm yields a host of functionalities. On one hand, it seamlessly supports edge computing capabilities, empowering the execution of computations closer to the data source. On the other hand, it accommodates device-to-cloud

communication (I2IM), ushering in the potential for real-time data exchange between devices and cloud-based resources. Simultaneously, the architecture fosters peer-to-peer communication (I2I), facilitating direct information exchange among devices.

Embedded within this framework are computing platforms that hold a pivotal position. These platforms undertake the essential tasks of processing and interfacing with sensors and controllers. In essence, they form the dynamic hub where data is processed, transformed, and made available for further analysis or dissemination.

3. Intelligent Traffic Signal Control

3.1. Dynamic Traffic Phasing

In Fig. 4, a visual representation unfolds, elucidating the sequential progression of phases within the intersection. On the top the phases are exemplified.

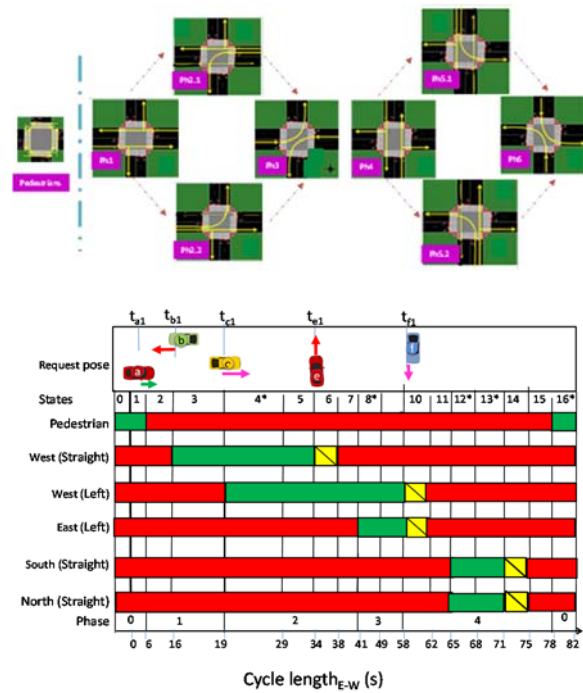


Fig. 4. Requested phasing of traffic flows.
* Adaptive sequences.

This orchestrated flow adheres to a structured cycle length comprising six distinct phases. Each of these phases is further intricately subdivided into 16 discrete time sequences or states, delineating a comprehensive temporal framework for the intersection's operation.

An essential observation to highlight is that states designated with an asterisk (*) hold a dynamic quality, representing movable states that adapt in response to

varying traffic demands within the cycle. Specifically, sequences marked with the numbers "0", "1", and "16" denote the exclusive pedestrian phase, signaling a dedicated time interval for pedestrian movement.

Furthermore, the synchronization of the cycle initiates with sequence "1", marking the commencement of the orchestrated flow of phases. Within this cycle, phases one through four are each allocated sequence spanning from "2" to "15". These sequences within these phases play a pivotal role in meticulously regulating the traffic flow, ensuring a structured and efficient movement of vehicles through the intersection.

3.2. V-VLC Adaptive Traffic Control

To code the information, an On-Off keying (OOK) modulation scheme was used, and it was considered a synchronous transmission based on a 64-bits data frame. Each infrastructure is equipped with white tetrachromatic LEDs, making it possible to transmit four signals simultaneously (Fig. 2b). So, all that is needed is a receiver that actively filters each of the channels, and a four-fold increase in bandwidth is possible. Each of the RGBV signals sent has calibrated amplitude that defines it. Because each VLC infrastructure has four independent emitters, the optical signal generated in the receiver can have one, two, three, or even four optical excitations, resulting in 2^4 different optical combinations and 16 different photocurrent levels at the photodetector [18]. Filtering is achieved by the PINPIN demultiplexer, which receives the combined OOK signal and through prior knowledge of the calibrated amplitudes is able to decode the sent message.

As an example, in in Fig. 5 Vehicle c_1 (Fig. 2), receives three MUX signals as it crosses the intersection, during Phase2. This vehicle, driving on the left lane (#8 E), was the sixth to ask permission to cross the intersection it receives order to enter the intersection in pose #8E, turns left (#1NE) and keeps moving in this direction across position #1 toward the North exit (#4N). In the right side, the received channels are identified by its 4-digit binary codes and associated positions in the unit cell. On the top the transmitted channels packets [R, G, B, V] are decoded. The environment is also inserted to guide the eyes.

As exemplified in the top part of Fig. 5, the frame is divided into several blocks. The first block is the synchronization block. The synchronism always considers the same sequence of bits for all transmitters in a pattern [10101], having as a second purpose the identification of the maximum possible amplitude at reception. By knowing the maximum amplitude received it is possible to identify the footprint region [18]. With this information and with the help of the calibration signal, the location of the vehicle in its cell is defined. The next two blocks, gives the location (x, y coordinates) of the emitters inside the array ($X_{i,j}$). Cell's IDs are encoded using a 4 bits binary representation for the decimal number. The δ block

(steering angle (δ)) completes the pose in a frame time $q(x, y, \delta, t)$. Eight coded steering angles along the cardinal points gives the car direction. The next block (R) identifies the message type, which can be a "request" [00], a "response" [01] or another message type. The Flag (F) is a bit indicating whether there is vehicle identification in the following bits or not. Its purpose is to alert the decoder that the following bit sequence corresponds to the vehicle identification rather than the payload. ID block is the temporary identification of the vehicle, decided and provided by the infrastructure on the "response" message and order the request message at the intersection. Here, 5 bits are considered because a maximum of 32 vehicles per lane (8 routes, 4 lanes) are expected at message distance (20 m). The last is the traffic message. It is the body of the message, and may include other information such as the road condition, average-waiting time, and weather conditions, among others. EoF Bit or sequence of bits defines the end of the frame. In this case, the sequence [0110] was considered.

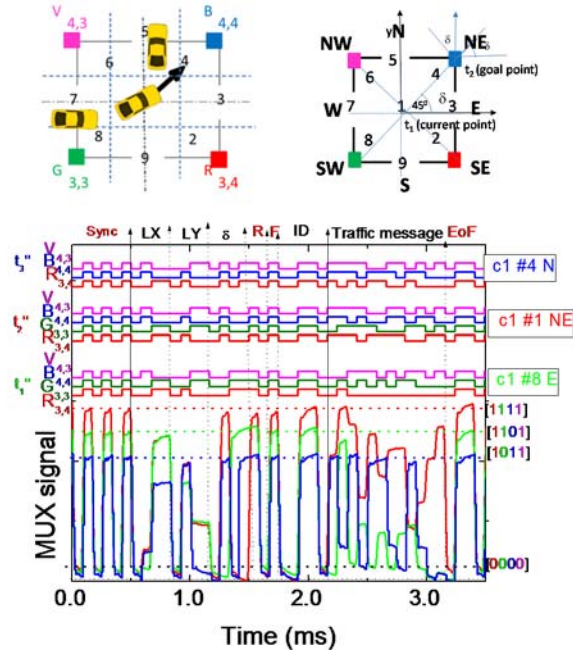


Fig. 5. MUX signals and assigned decoded poses inside intersection 1 acquired by vehicle c_1 , entering (t_1'), crossing (t_2') and exit (t_3'). On the top the transmitted channels packets [R, G, B, V] are decoded. The insert visualizes the environment.

3.3. Dynamic Traffic Flow Control Simulation

The simulated environment for the SUMO simulation, illustrated in Fig. 2, models a 4-way intersection with two lanes on each arm. The arms converge on the intersection from the cardinal directions, creating a total of eight lanes. Each arm has a length of 100 meters. On every arm, each lane specifies the allowable directions for vehicles. The

right lane permits vehicles to turn right or proceed straight, while the left lane confines vehicles to left turns only.

To manage traffic flow, a traffic light system is in place at both intersections. The Intersection Manager (IM), also known as the agent, controls this system. The IM oversees approaching traffic by coordinating the timing of traffic signals, ensuring efficient and safe movement within the intersection. Fig. 6a labels the Traffic Lights (TL), Lanes (L), and possible trajectories of vehicles. In Fig. 6b, the state representation for the west arm of the intersection is demonstrated for a simulated timeframe.

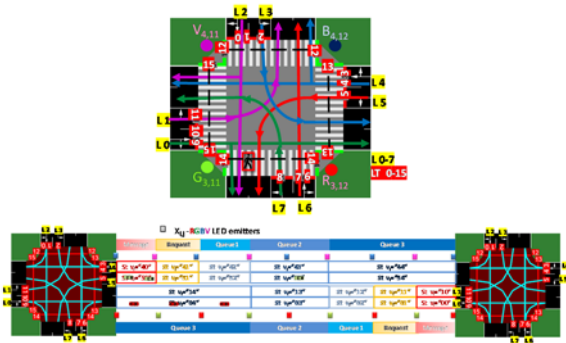


Fig. 6. a) Traffic Lights' (TL) and Lanes(L) identification and vehicles' possible trajectories. b) State representation for the west arm of the intersections. Traffic Lights' (TL; 0-15), Lanes (L;1-7.).

Each arm of the intersection is partitioned into discrete cells representing "response," "request," and "queue" zones to detect vehicle entry into incoming lanes. Before reaching the intersection's stop line, there are four cells (0/message, 1/request, 2, 3/queues) per lane. Each lane (L/0-7) is associated with a dedicated traffic light (TL/0-15), resulting in a total of 32 state cells during simulation.

In the simulation, an array is employed to store the state of all vehicles at a specific time, with unique states assigned to each vehicle. The state of a vehicle, labeled as " v_i " where " i " corresponds to the crossing request order, is expressed as a two-digit string. The initial digit designates the lane in which the vehicle is located, while the second digit indicates its position within that lane. For instance, the states of leaders a_1 (in lane L0) and b_1 (in lane L5) would be denoted as $v_1 = "00"$ and $v_2 = "50"$, respectively.

The training process is structured into multiple episodes, with the user typically specifying a total number of episodes exceeding 100. Each episode represents a training iteration, during which actions are executed based on the activation of specific lanes by the traffic light system, following predetermined timings during the green phases (refer to Fig. 4). The yellow phase is set at four seconds, and the green phase lasts for eight seconds. If the action taken in the current agent step (t) mirrors the action taken in the previous agent step ($t-1$), there is no yellow phase, and

the current green phase is extended. However, if the action selected in the current agent step differs from the previous action, a 4-second yellow phase occurs between the two actions. This mechanism facilitates smoother transitions between different actions and provides time for vehicles to respond to changing traffic signals. In the SUMO simulation, one simulation step corresponds to one second, resulting in eight simulation steps between two identical actions.

The reward (r) serves as the environment's response to the agent's decision, quantifying how favourable or unfavourable the agent's action was in terms of achieving desired objectives or optimizing performance metrics. This reward signal is essential for guiding reinforcement learning algorithms, helping the agent improve its decision-making abilities over time.

To incentivize the agent effectively and enhance intersection efficiency, it's crucial to base the incentive on a traffic efficiency performance metric. This metric enables the agent to assess whether its actions have led to a reduction or improvement in intersection efficiency. In the presented scenario (Fig. 2), the Intersection Manager (IM) receives requests for intersection access from leading vehicles at different times (t_{xl} in Fig. 4). Vehicle-to-Infrastructure (V2I) information provides the IM with precise location and speed data of leader and follower vehicles through V2V communication. This data allows the IM to anticipate the initial arrival times and speeds of vehicles at various sections of the intersection.

For vehicle circulation, it's assumed that all vehicles are moving at an average speed of 10 m/s. However, when vehicles approach the traffic light at the cycle's beginning, during pedestrian evacuation, their speed decreases to 5 m/s. Considering this speed change, it's estimated that approximately three seconds of green light are needed for each vehicle to pass through the traffic light. By incorporating this information into the incentive system, the agent can be motivated to make decisions that optimize traffic flow, minimize delays, and ensure efficient utilization of green light time, ultimately improving overall intersection efficiency.

3.4. Adaptive V-VLC Traffic Control Evaluation

Using the application programming interface (API) provided by SUMO, it is possible to interface with external programs and interact with the simulation environment. SUMO provides various statistics related to the overall traffic flow and provides various outputs, such as diagrams illustrating the duration of each state or color of the traffic lights throughout the simulation. Based on the simulation scenario depicted in Fig. 2, a state diagram was generated using SUMO simulation. Fig. 7a and Fig. 7c show the phase diagrams for the two connected intersections, TL1 and TL2. The SUMO environment is illustrated in Fig. 7b.

The simulation scenario was adapted from a real-world environment in Lisbon [21, 22], and it considers the presence of roads that impact the traffic flow at both intersections. These roads, referred to as the target road, have a dynamic influence on the traffic flow, and the impact of the historical traffic state from other roads on the target road is limited in time. Here, the E-W arm was considered as a target road. The transmission of traffic flow and traffic waves measures the time duration for which the traffic state of other roads affects the target road within the same period. As traffic continuously enters the system, the composition of the traffic flow on the target road undergoes changes over time. To improve the traffic flow conditions, a modification was made to the initially proposed phases (as shown in Fig. 4).

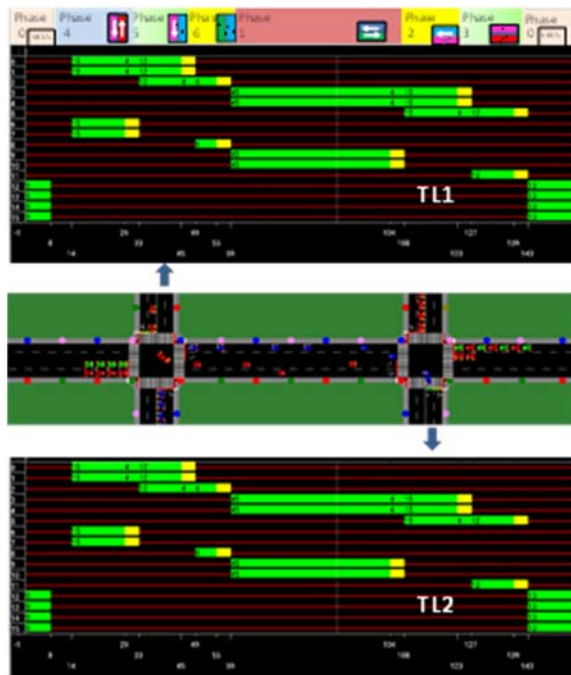


Fig. 7. State diagram resulting in two coordinated intersections (TL1 and TL2). On the top an insert of environment and the color phasing is inserted. At the middle the environment is draft.

The modification involved an immediate transition from the pedestrian phase (Ph0) to the N>S phase (Ph4), followed by the remaining phases in both intersections. This change in phase order was found to enhance the traffic flow conditions in the simulation. By adjusting the phase sequence and optimizing the traffic light control strategy based on the simulation results, it is possible to achieve improvements in traffic flow, reduce congestion, and enhance overall intersection performance.

In Fig. 8, a comparison is presented between the queue (halting) and average speed observed every second in SUMO/VLC (Simulation of Urban MObility with Visible Light Communication) for a

130-second cycle. The simulation assumes a saturation flow of 2500 vehicles per hour.

The results demonstrate that on the regulated roads, there are typically no congested conditions occurring in each new cycle. The queue of vehicles in the first section of the demand acts as an integrator, meaning it accumulates vehicles and its length increases as vehicles enter the section. This becomes critical when the queue approaches the capacity of the link road. In the unsaturated regime, which assumes that all vehicles in the queue leave the target road by the end of the sampling time, the queue of vehicles is always zero. However, when the red light is activated, a maximum queue of vehicles is generated since all vehicles in the queue are held back. This analysis provides insights into the behavior of traffic flow and queue dynamics within the simulated environment. It demonstrates the impact of traffic lights and their timing on the accumulation and dispersal of vehicles at different sections of the road network. Fig. 9 represents the reward obtained, after the training, when the network was tested. The test was performed for the two intersections scenario with independent crossings. The results obtained from the experiment indicate that as the number of action steps increases, the cumulative rewards become more positive. This demonstrates that the agent learns to make better decisions over time during the test. The feasibility and benefits of creating a dynamic system that can adapt to specific traffic scenarios are evident in the results. Safety and privacy are crucial requirements for the V-VLC system.

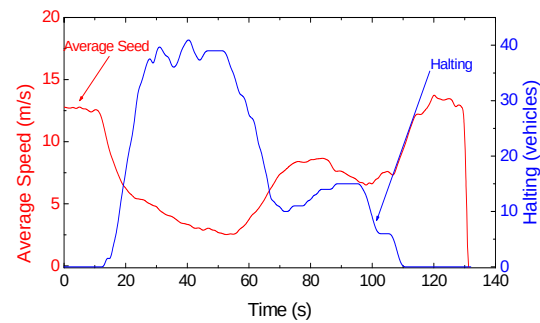


Fig. 8. Average speed and halting along a cycle.

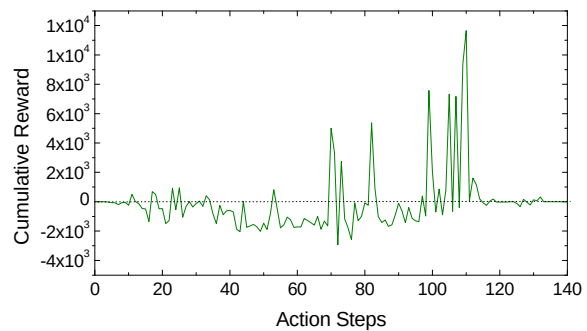


Fig. 9. Cumulative reward.

To bolster security, upcoming advancements should prioritize the enhancement of coding techniques to guarantee that exclusively authorized receivers can decipher secure request/response messages. These security measures extend deep into the fabric of the physical transmission process, particularly within the Line of Sight (LoS) channel. In this context, potential eavesdroppers are rendered passive observers, devoid of any access to transmitted information.

One promising avenue for augmenting security entails harnessing the positional data of streetlamps to deduce the flow of vehicular traffic. This innovative approach holds the potential to obviate the necessity for traditional certificates or passwords within the network. Instead, it paves the way for a paradigm shift toward statistical secrecy. By weaving this statistical approach into the security framework, the reliance on explicit authentication measures can be alleviated, while concurrently fortifying the layers of protection against unauthorized access.

In essence, the trajectory for fortifying security within the system rests upon refined coding techniques, the intrinsic security attributes of the LoS channel, and the intelligent utilization of positional information for traffic flow analysis. This approach promises to yield enhanced security measures, ushering in a future where secure communication flourishes within the framework of advanced vehicular systems.

4. Conclusions

V-VLC technology integration in connected cars offers significant improvements to urban traffic networks by integrating traffic signal control with driving behavior. This innovative system utilizes a queue/request/response approach for efficient intersection management while providing real-time monitoring of queues and messages. Through detailed data collection, V-VLC technology enables dynamic adjustments to traffic light phases and durations, leading to reduced travel times and minimized waiting for drivers. Furthermore, V-VLC enhances safety by directly monitoring crucial areas such as queue formation, ensuring a safer and more efficient traffic flow.

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Automated Guidance Vehicles Controlled by Visible Light Communication

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Abstract: The advent of devices with wireless communication capabilities has generated increased interest in indoor navigation. Several wireless technologies have been proposed for indoor location, as the traditional Global Positioning System has a poor performance in a closed space. This research proposes the use of an indoor localization system based on Visible Light Communication (VLC) to support guidance and operational tasks of Autonomous Guided Vehicles (AVG). The research is focused on the development of the guidance VLC system, transmission of control data information and decoding techniques. Trichromatic white LEDs are used as transmitters and photodiodes with selective spectral sensitivity are used as receivers. The downlink channel establishes an infrastructure-to-vehicle link (I2V) and provides position information to the vehicle. The decoding strategy is based on accurate calibration of the output signal. Characterization of the transmitters and receivers, description of the coding schemes and the use of different modulations will be discussed.

Keywords: Visible light communication, Autonomous guides vehicle, Indoor positioning, Guidance, On Off keying, Manchester.

1. Introduction

Automated guidance vehicles (AGV) are mobile robots powered by electricity that operate independently [1]. The navigation of the AGV can follow a fixed route or a free ranging route. AGVs are now found in all types of industries, with the only restrictions on their use mainly resulting from the dimensions of the goods to be transported or spatial considerations [2].

Several technologies can be used to provide guidance to the AGVs, ranging from magnetic, optical or radio-based technologies. Visible Light Communication (VLC) is an optical wireless communication technology operating in the visible range of the spectrum, that provides several

advantages, such as, license-free spectrum, high-speed, immunity to electromagnetic radiation and security, among others [3, 4].

VLC can be implemented using phosphor coated blue LEDs and red-green-blue (RGB) LEDs. RGB LEDs provide higher speed, as their operation is not dependent on the slow decay of the phosphor. Besides, they allow the use of the three wavelengths to transmit different data streams simultaneously. VLC provides several applications ranging from short (a few meters) to medium range (few meters to few kilometers) distances, which includes data transmission for Short range IoT, Smart Homes, Light Fidelity, Under Water communication, Vehicular Networking, among others [5].

As it can be used in localization applications, in this paper we propose the use of an AGV guidance system based on Visible Light Communication (VLC) able to provide information on the current position of the vehicle and enable it to navigate autonomously. VLC [6].

This system uses white tetrachromatic LEDs operating as optical signal transmitters and a-SiC:H pinpin heterostructure as receivers [7-9]. These photodetector devices exhibit active filtering, amplification, and selective sensitivity [10, 11] in the visible range. Different visible wavelength signals are encoded in the same optical transmission path, so the device multiplexes the different optical channels, performs filtering processes (amplification, switching, and wavelength conversion), and outputs a multiplexed signal [12, 13]. The modulated signal transmitted by each emitter can be recovered by decoding this signal [14, 15]. For a reliable calibration curve, each photocurrent level must be accurately regulated [16, 17]. To decode the multiplexed signal, we will use On-Off keying modulation and Manchester codes [18]. This system is intended for indoor positioning and guidance of autonomous guided vehicles (AGV) used to transfer materials from pickup places to drop off places [19] inside an automated warehouse. The system attends bidirectional communication with links Infrastructure-to-Vehicle (I2V) and Vehicle-to-Infrastructure (V2I). The link I2V provides an indoor localization information inside the warehouse enabling navigation services [20]. Operational information for operation inside the warehouse is also transmitted to the AGVs. The links V2I and V2V provide cooperation services to enhance system performance [21-23].

The indoor localization system involves optical wireless communication, computer-based algorithms, smart sensors, and optical sources network, which constitutes a transdisciplinary approach framed in cyber-physical systems.

This paper is an extension of work originally presented in the 9th International Conference on Sensors and Electronic Instrumentation Advances (SEIA' 2023) [24] that provided preliminary results of AGV guidance supported by VLC.

2. VLC System Description

This work describes the use of VLC for positioning and guidance in indoors environments based on VLC to be used for navigation of AGVs in automated warehouses. Based on VLC technology, the AGV and the infrastructure can establish bidirectional communication using two separate channels (Fig. 1), the uplink (vehicle to infrastructure or V2I) and the downlink (infrastructure to vehicle or I2V). Additional links can be established among the vehicles (vehicle to vehicle or V2V). This paper deals with the I2V channel.

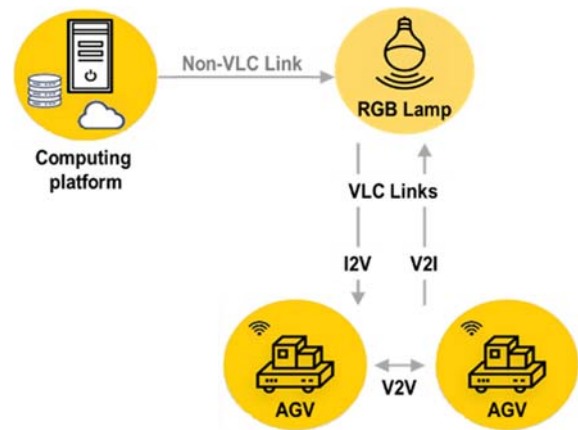


Fig. 1. Communication channels.

Lighting and communication are provided simultaneously by the infrastructure through optical emitters based on tetra-chromatic LED white lamps at the warehouse ceiling.

2.1. VLC Transmitter

The VLC transmitter uses commercial RGB LEDs provide three different wavelengths, centered on the red, green, and blue bands (620 nm, 530 nm and 470 nm) with standard linewidths (ranging from 24 nm to 38 nm), high luminous intensity (in the range from 340 mcd up to 980 mcd) and wide half intensity angle (120 °). Along the indoors space, LED bulbs provide simultaneous lighting and communication, defining navigation cells (Fig. 2).

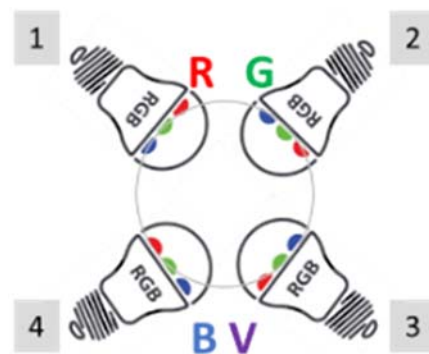


Fig. 2. VLC transmitters.

Each VLC transmitter defines a unit navigation cell containing the optical signals transmitted by each communication channel.

2.2. VLC Channel

The VLC channel was modeled using Lambertian beam distributions for each LED assuming

line-of-sight conditions. Fig. 3 illustrates a 2D representation of the coverage signal due to four transmitters positioned in squares. The map representation is normalized to the maximum intensity at the center, after evaluating the delivered optical power in dBm. There is a strong signal at the center of the region because all four emitters contribute to it. Only three emitters contribute to the signal at the corners, while only two emitters contribute to the signal at the sides. As a result, the received signals inside the unit navigation cell determine the spatial coverage of the VLC transmitter, which allows for more accurate positioning within this delimited area. Each of these regions constitute the footprints of the cell and are labelled from #1 to #9 as indicated in Fig. 3.

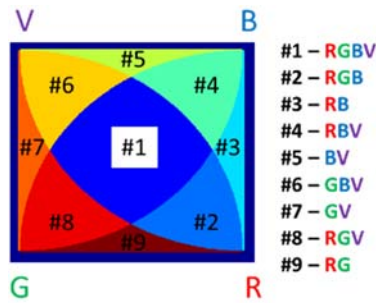


Fig. 3. Coverage produced by the VLC transmitter and footprints enabled by each emitter's signals.

2.3. VLC Photodetector

The VLC receiver used in the VLC system is a photodiode composed of a pinpin heterostructure based on a-SiC:H/a-Si:H. In the receiver unit, the photodetector is a pin-pin heterostructure based on a-SiC:H/a-Si:H [25]. Since its design was tailored to address a wavelength sensitive device in the visible spectrum, it exhibits active filtering and amplification properties as well as selective sensitivity. In this photodiode, two a-Si:H pins are mounted on top of one a-SiC:H pin, which allows the device to be used over the full visible spectrum. The device is operated under reverse bias to improve collection efficiency. Steady state optical bias using short visible wavelength (400 nm) is used to improve amplification of the longer wavelengths and attenuation of the short ones.

The spectral sensitivity of the sensing photodiode shows that under back violet background illumination the gain is high at short wavelengths (blue light) and decreases for longer wavelengths (green and red). The device behaves as a short-pass filter. Under front violet background light, the device works as a long-pass filter for wavelengths above 500 nm, blocking the shorter wavelengths. The shift of the irradiation device side (front/back) allows tuning the short- and long-spectral regions, while the medium region (475 nm – 530 nm) can only be tuned by using both active filters. Under front illumination the red part of the spectrum

is enhanced while under back illumination the main enhancement occurs for the blue signal (Fig. 4).

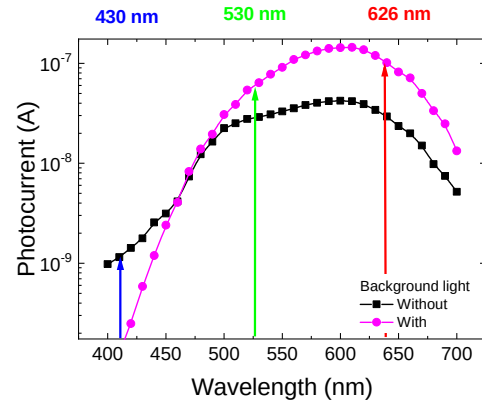


Fig. 4. Spectral sensitivity of the VLC receiver.

In this photodiode, two a-Si:H pins are mounted on top of one a-SiC:H pin, which allows the device to be used over the full visible spectrum. The device is operated under reverse bias to improve collection efficiency. Steady state optical bias using short visible wavelength (400 nm) is used to improve amplification of the longer wavelengths and attenuation of the short ones.

2.4. VLC Data Coding

Specific data codes are needed to define the communication link and the type of message to be transmitted. In every channel, it was used synchronous transmission based on a data frame of fixed length.

Synchronization of the frames can be enabled using different approaches. The SoT is placed at the beginning of the frame and the EoT at the end. Then a TYPE block with 4 bits is used to define the type of message (0000 in request/acknowledge mode, 0011 in standard/update mode). The complete structure of the data frame has the format displayed in Fig. 5.

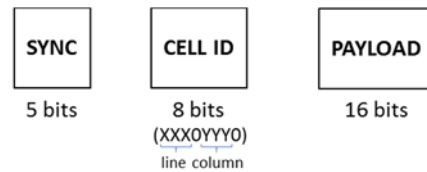


Fig. 5. Data frame structure of the VLC communication channel.

The block labelled GEO-LOCATION (16 bits) identifies the cell and footprint. The cell identification is coded as XXX0YYY0, where XXX addresses the line and YYY the column of the cell. The footprint is produced by coding the R and B emitters with four bits set to 1 and four bits set to 0, while the R' and B'

emitters are coded with two bits set to 1 and two bits set to 0, and then two bits set to 1 and two bits set to 0. The 36 bits MESSAGE block addresses specific instructions transmitted to the user and dependent on the type of communication mode.

2.5. VLC Data Modulation

Data transmission demands the use of a specific modulation scheme. Here we will use both OOK and Manchester. While OOK is a valuable modulation scheme in VLC due to its low complexity and ease of implementation, it still severely limits data rates, which is further strengthened by systems that use different dimming levels.

An evaluation of OOK and Manchester coding VLC modulation techniques with differing levels of complexity is presented in this paper. OOK assigns different levels of amplitude to each of the data bits we wish to modulate, with a bit time duration of bit. Manchester assigns both levels to each bit, one per bit time duration bit, but it is the transitions from on to off (“on-off”) or off to on (“off-on”) that distinguish between ‘0’ and ‘1’ data bits.

In this paper the Manchester codes use the convention of considering “off-on” transitions as ‘0’s and “on-off” transitions as ‘1’s. The representation under OOK and Manchester modulations is shown in Fig. 6.

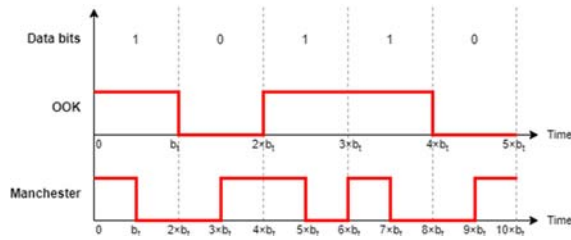


Fig. 6. Time domain representation of data bits in OOK and Manchester.

Data transmission in Manchester is halved since it takes twice as long to transmit the “on” or “off” pulses that encode the same information as in OOK. In contrast, Manchester forces at least one level transition per bit of data, leading to lower levels permanence, even in long sequences of the same bit.

2.6. Decoding approach of the VLC signal

With each optical emitter data transmission, a multiplexed signal is produced at the photodetector. Due to the VLC transmitter’s four independent emitters, the out-put optical signals can combine one, two, three, or four optical excitations. If the driving currents for each emitter are adjusted correctly, this can produce 16 different optical combinations and therefore 16 different photocurrent levels.

The bit decoding of the multiplexed signal corresponds to the correct assignment of each photocurrent level to the respective optical excitation. This is provided using a previous system calibration, by adjusting the photocurrent levels of the multiplexed signal.

The on-off states of the calibration signal and respective label of each photocurrent level are summarized in Table 1.

Table 1. On-off states of the calibration signal and respective levels.

	R	G	B	V
d0	Off	Off	Off	Off
d1	Off	Off	Off	On
d2	Off	Off	On	Off
d3	Off	Off	On	On
d4	Off	On	Off	Off
d5	Off	On	Off	On
d6	Off	On	On	Off
d7	Off	On	On	On
d8	On	Off	Off	Off
d9	On	Off	Off	On
d10	On	Off	On	Off
d11	On	Off	On	On
d12	On	On	Off	Off
d13	On	On	Off	On
d14	On	On	On	Off
d15	On	On	On	On

The coding of the calibration signal using either OOK or Manchester is summarized, respectively, in Table 2 and Table 3, where the ‘0’ state for the off states and ‘1’ for the on states of the LED. In the Manchester coding each on or off state is represented using two bits.

Table 2. Decoding levels in OOK calibration curves.

	R	G	B	V
d0	0	0	0	0
d1	0	0	0	1
d2	0	0	1	0
d3	0	0	1	1
d4	0	1	0	0
d5	0	1	0	1
d6	0	1	1	0
d7	0	1	1	1
d8	1	0	0	0
d9	1	0	0	1
d10	1	0	1	0
d11	1	0	1	1
d12	1	1	0	0
d13	1	1	0	1
d14	1	1	1	0
d15	1	1	1	1

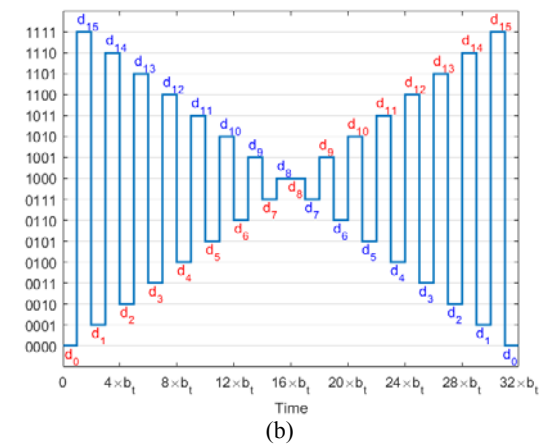
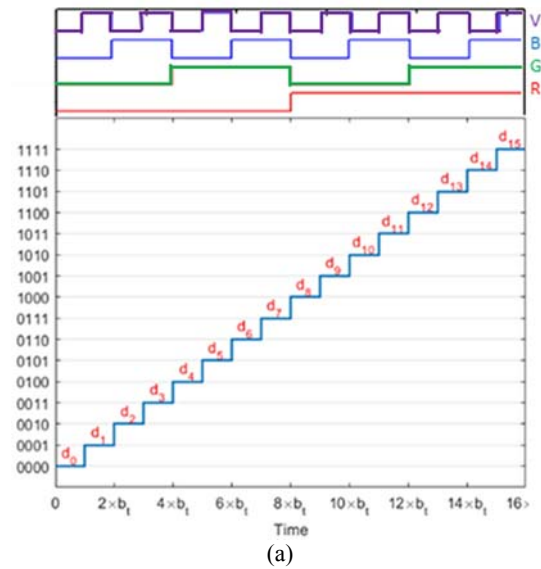
Since Manchester codes demand the double of the bits to encode the same information, each ‘on’ or ‘off’ state of the LED produces two adjacent photocurrent levels.

Table 3. Decoding levels in Manchester calibration curves.

		R	G	B	V
d0	d15	01	01	01	01
d1	d14	01	01	01	10
d2	d13	01	01	10	01
d3	d12	01	01	10	10
d4	d11	01	10	01	01
d5	d10	01	10	01	10
d6	d9	01	10	10	01
d7	d8	01	10	10	10
d8	d7	10	01	01	01
d9	d6	10	01	01	10
d10	d5	10	01	10	01
d11	d4	10	01	10	10
d12	d3	10	10	01	01
d13	d2	10	10	01	10
d14	d1	10	10	10	01
d15	d0	10	10	10	10

Fig. 7 shows the calibration signal with 16 levels assigned to each input optical state. The optical signal transmitted by each emitter is displayed on top of the picture. The multiplexed signal is shown under OOK and Manchester modulations.

In OOK modulation (Fig. 7(a)), the set of 16 distinct calibration levels produce a staircase-like shape in the MUX signal, each associated with a particular optical excitation type. The left side of Fig. 7(a) indicates the correspondence of the optical state RGBV and the level label (d_i , $i = 0, 1, \dots, 15$) using binary notation. When using Manchester codes (Fig. 7b), the same data bit sequence takes twice as long as OOK, which halves the data rate. The calibration curve takes on a very different shape. This occurs because of how Manchester uses 2 bits to represent each data bit, leading to the calibration curve having a shape of two alternating OOK calibration curves with one rising branch and the other falling branch.

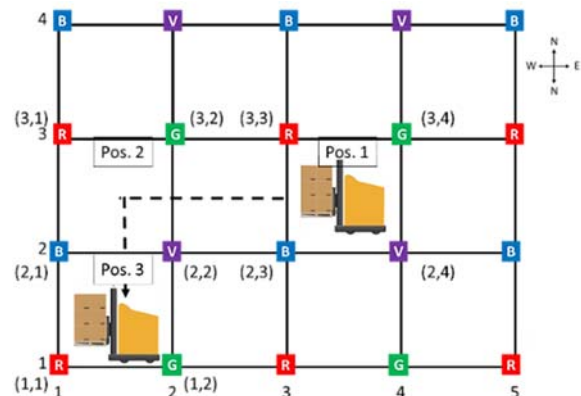
**Fig. 7.** Layout of the warehouse space including VLC transmitters and AGV successive positions (initial, intermediate and destination).

3. Results and Discussion

An illustration of the proposed study involving the comparison of both modulations and the results obtained using the described methodology is included in this section.

3.1. Case Study

The case study used in this work the AGVs can move in a linear warehouse configuration with racks on either side of the aisle for picking up materials, as displayed in Fig. 8. A matrix notation that specifies the row and column of the navigation cells is used to number the cells. The AGV at the initial position (position 1) is directed to move to an intermediate position (position 2) and then to the destination (position 3).

**Fig. 8.** Layout of the warehouse space including VLC transmitters and AGV successive positions (initial, intermediate and destination).

As the AGV moves, it establishes V2I communication. Even so, this paper will not address it, since its focus is on the analysis of the I2V multiplexed signal.

3.2. VLC Signal

In Fig. 9 it is displayed the photocurrent signal measured inside footprint #1 (region covered by the four optical signals RGBV) at position 1 using the OOK and Manchester modulations. The blocks SoH and EoT provide the necessary synchronization between frames.

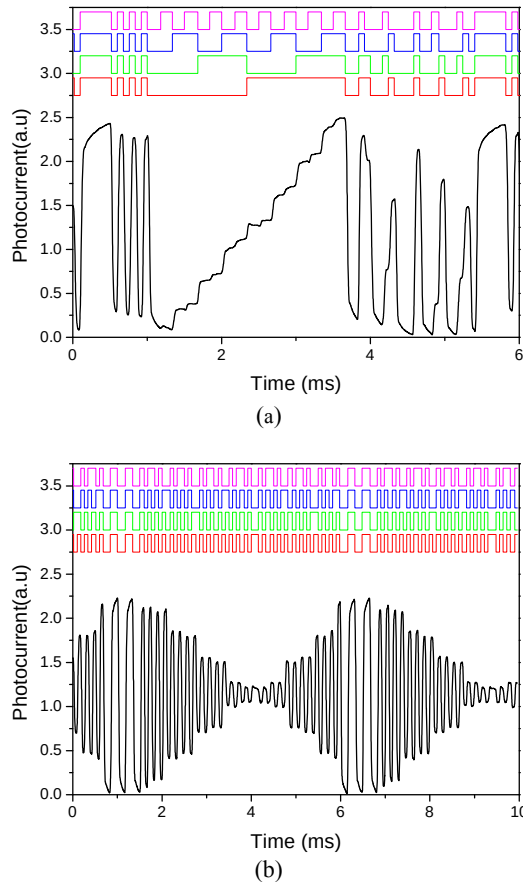


Fig. 9. Transmitted data message at the intermediate position (2) using the modulation: a) OOK; b) Manchester.

Both measurements show that the presence of these blocks leads to maximum values of the photocurrent, since all emitters are on simultaneously. According to the photocurrent levels obtained in each signal, the optical excitation level is dependent on the footprint region, which hosts the AGV, as well as the bit sequence transmitted by the active emitters.

The output resultant signal acquired by the receiver device shows different levels of photocurrent that can be assigned to the correspondent optical excitation. As the device exhibits capacitive effects, the photocurrent level exhibits a rising or falling slope, dependent whether the transition occurs from a lower to an upper level, or vice-versa. Consequently, this effect becomes more evident when two or more adjacent bits have the same state.

In OOK modulation as the bit states are simply represented by '0's or '1's, it is possible that the signal

contains many similar adjacent symbols ('1s' or '0s'), which reinforce this effect. It is clear from Fig. 9(a) that, for example, the upper levels achieved by every single 'on' bit are lower than those obtained by two adjacent 'on' bits. This may induce errors in the bit decoding process.

When using Manchester coding, Fig. 9(b) each state is represented with a transition between different states. Therefore, no more of two similar bits occur during the transmission and the limitations imposed by the capacitive effects of the sensing device are attenuated.

On the other hand, frame synchronization that is established by the heading block transmitted in the beginning of each frame is crucial to ensure correct data transmission. As this block is composed of a sequence of 5 specific states ('on'-'off'-'on'-'off'-'on') followed by the identification labels of the transmitting cells, the correct identification of the block among the transmitted frames is not a hard issue to complete successfully.

Nevertheless, under Manchester coding a level transition is less likely to coincide with the start of a frame due to the halved data rate, or even with the start of a data bit since a transition is forced to occur in the middle of each data bit.

The decoding strategy involves direct comparison of the signal levels with the calibration signal is achieved by assigning the bit level to the level closest to the calibration signal. Bits represented by close values may be improperly decoded. This is especially important when using OOK modulation, since capacitive effects can mislead the decoded level, whereas Manchester modulation minimizes this problem. Parity check bits are a possible solution to reduce the bit error decoding.

4. Conclusions

The proposed application focuses on the use of VLC based system to support the guidance of AGV. The physical layer of the communication system was fully characterized, from transmitters and receivers to the propagation channel modelling and data coding. Two modulation techniques, OOK and Manchester, were used to infer bit decoding performance. As the multiplexed signal results from multiple optical channels, its waveform is complex. It is necessary to use decoding techniques to determine the correct bits transmitted by each optical channel. Improvements to the decoding technique include parity check error control.

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Enhancing Building Guidance: A Visible Light Communication-Based Identifier (ID) System

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Abstract: This paper introduces an innovative approach employing Visible Light Communication (VLC) to generate landmark-based routes and alert instructions, enhancing support for individuals during wayfinding activities. The system utilizes ceiling luminaries as transmitters, broadcasting map information, alerts, and path messages. Through real-time data collection by optical receivers, users are provided with the most efficient routes to navigate around congestion. Tetrachromatic identifier white sources are employed for lighting, featuring various data channels. Data is encoded, modulated, and transformed into light signals, with mobile optical receivers capturing and interpreting this information, allowing users to interact bidirectionally. The system calculates optimal routes for static or dynamic destinations, including buddy wayfinding services. Results demonstrate the system's capability to enable self-location, deduce travel direction, and facilitate efficient navigation towards both static and dynamic locations.

Keywords: Visible Light Communication (VLC), Geolocation, Indoor navigation, Bidirectional communication, Wayfinding, Optical sensors, Transmitter/receiver.

1. Introduction

In the realm of modern technology, visible light has emerged as an innovative and versatile tool for creating identification systems with a unique twist. The concept revolves around harnessing the power of light signals, carefully choreographed in timed sequences and divided into spatial beams, to serve as an Identifier (ID) system for building recognition. This groundbreaking approach leverages the capabilities of LED arrays, enabling bidirectional communication channels where light takes on the roles of both down-link and up-link channels.

The implications of this novel technology are vast and far-reaching. With its ability to encode

information through modulated light signals, it finds applications in diverse domains such as positioning, navigation, security, and mission-critical services. This cutting-edge communication paradigm is known as Visible Light Communication (VLC), [1] a data transmission technology that seamlessly integrates into indoor environments, making use of existing LED lighting infrastructure with minimal modifications [2, 3]. VLC has become the development direction of the next generation communication network with its huge spectrum resources, high security, low cost, and so on [4, 5].

One of the standout features of this technology lies in its adaptability. By employing white polychromatic LEDs, a phenomenon known as Wavelength Division

Multiplexing (WDM) comes into play, enabling the simultaneous transmission of multiple data streams at different wavelengths. This ingenious approach effectively increases the data transmission rate, allowing for more information to be conveyed within a given timeframe.

A pivotal aspect of this innovative system is the development of a WDM receiver that capitalizes on light-controlled filters. This receiver is designed to decode the intricate information carried by the multiplexed signals. Through the process of multiplexing, filtering, and decoding, the encoded signals are meticulously unraveled, resulting in the accurate recovery of the transmitted information [6, 7].

In summary, the convergence of visible light, LED arrays, and sophisticated data transmission techniques has birthed a revolutionary approach to identification and communication within building environments. As we delve deeper into the intricacies of this technology, we uncover its transformative potential to reshape various industries and propel us into an era of more efficient, secure, and intelligent systems.

In this paper, a VLC based guidance system to be used by mobile users inside large buildings is proposed. After the Introduction, in Section 2, a model for the system is proposed and the communication system described. In Section 3, the main experimental results are presented, downlink and uplink transmission is implemented and the best route to navigate calculated. In Section 4, the conclusions are drawn.

2. VLC System Model

The main goal is to specify the system conceptual design and define a set of use cases for a VLC based guidance system to be used by mobile users inside large buildings.

2.1. VLC Emitter and Receiver Modules

The system model is structured around two primary modules: the transmitter and the receiver, illustrated in Fig. 1. The functionality of these modules is key to the successful operation of the technology.

The first of these modules, the transmitter, assumes the crucial role of transforming data from the sender into an intermediary representation in the form of bytes. These bytes serve as an intermediate step before they are translated into light signals by the transmitter.

In addition to robustness of electronic devices, modulation is imperative for the viability and performance of VLC systems. Data from the sender is converted into an intermediate data representation, byte format, and converted into light signals emitted by the transmitter module. The data bit stream is input to a modulator where an ON-OFF Keying (OOK) modulation is utilized. On the transmission side, a modulation and conversion from digital to analog data

is done. The driver circuit will keep an average value (DC power level) for illumination, combining it with the analog data intended for communication. The visible light emitted by the LEDs passes through the transmission medium and is then received by the MUX device.

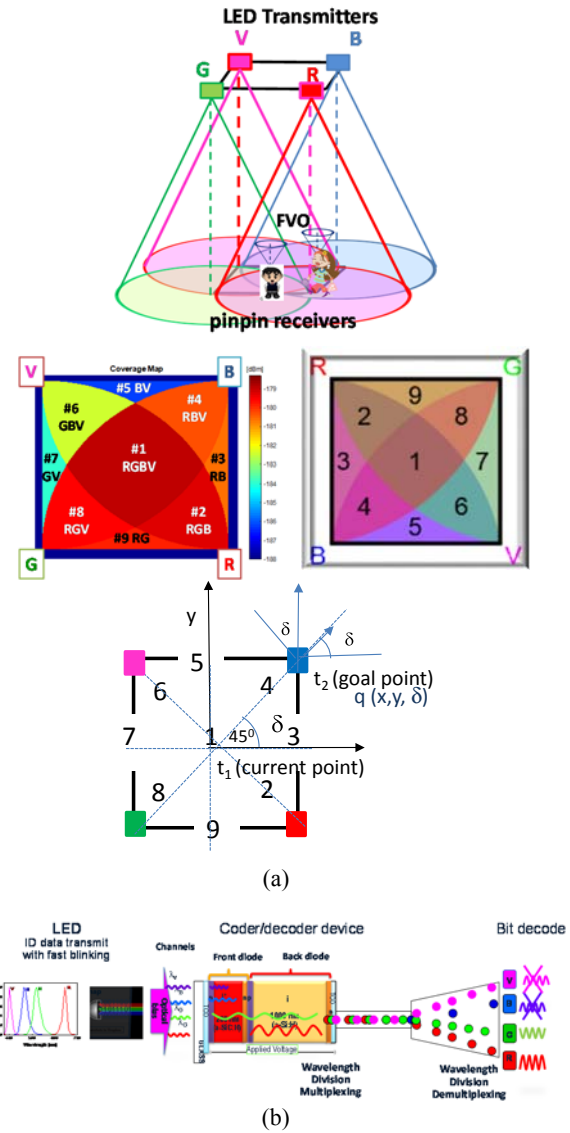


Fig. 1. a) Transmitters and receivers 3D relative positions, coverage map and footprints in the square topology; b) Configuration and operation of the pin/pin receiver.

To realize both the communication and the building illumination, white light tetra-chromatic sources (WLEDs) are used providing a different data channel for each chip. The transmitter and receiver relative positions are displayed in Fig. 1a. Each luminaire is composed of four polychromatic WLEDs framed at the corners of a square. At each node, only one chip is modulated for data transmission (see Fig. 1a), the Red (R: 626 nm, 25 $\mu\text{W}/\text{cm}^2$), the Green (G: 530 nm, 46 $\mu\text{W}/\text{cm}^2$), the Blue (B: 470 nm, 60 $\mu\text{W}/\text{cm}^2$) or the Violet (V, 400 nm, 150 $\mu\text{W}/\text{cm}^2$). A fundamental difference between VLC and regular

radio frequency (RF) communication is that VLC does not allow amplitude or phase modulation, and it must encode information by varying emitted light intensity. The LED can be dimmed ("off") when transmitting data bit '0' and at its maximum brightness ("on") when transmitting data bit '1'. This way, digital data is represented by the presence or absence of a carrier wave.

The conversion process involves taking the original data bit stream and feeding it into a modulator. This modulator employs an ON-OFF Keying (OOK) modulation scheme, which is a fundamental modulation technique widely used in communication systems. The essence of the OOK modulation lies in its binary nature. In this scheme, the presence of light signifies a binary "1" and its absence signifies a binary "0." By using this straightforward approach, the modulator effectively encodes the data onto the light signals. As the data bit stream varies, the modulator toggles the light emission on and off accordingly, translating the information into a sequence of light pulses.

Through this process, the transmitter converts the sender's data into light signals that will traverse the transmission medium. This methodology serves as the foundation for the subsequent stages of the communication process, as outlined in the system model.

The signal is propagating through the optical channel, and a VLC receiver, at the reception end of the communication link, is responsible to extract the data from the modulated light beam. In the receiving system, a MUX photodetector acts as an active filter for the visible spectrum. The integrated filter consists of a p-i'(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure with low conductivity doped layers [10] as displayed in Fig. 1b. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information. The obtained voltage is then processed, by using signal conditioning techniques (adaptive bandpass filtering and amplification, triggering and demultiplexing), until the data signal is reconstructed at the data processing unit (digital conversion, decoding and decision) [8, 9]. At last, the message will be output to the users. In order to receive information from several transmitters, the receiver must position itself so that the circles corresponding to the range of each transmitter overlap. This results in a multiplexed (MUX) signal that acts both as a positioning system and as a data transmitter. The grid sizes were chosen to avoid overlap in the receiver from adjacent grid points. The nine possible overlaps (#1-#9), defined as fingerprint regions are also pointed out for the unit square cell, in Fig. 1a.

In this system model, there are a few assumptions that should be noted: The channel state information is available both at the receiver and the transmitter; compared with the direct light, the reflected light is much weaker in the indoor VLC systems; only the Line OF Sight (LOS) path is considered and the multipath influence is not considered in the proposed indoor VLC system.

The received channel can be expressed as:

$$y = \mu hx + n, \quad (1)$$

where y represents the received signal, x the transmitted signal, μ is the photoelectric conversion factor which can be normalized as $\mu = 1$, h is the channel gain and n is the additive white Gaussian noise of which the mean is 0.

The LEDs are modeled as Lambertian sources (Fig. 1b) where the luminance is distributed uniformly in all directions, whereas the luminous intensity is different in all directions. The luminous intensity for a Lambertian source is given by Eq. (2) [11]

$$I(\phi) = I_N \cos(\phi)^m \quad ; m = \frac{\ln(2)}{\ln(\cos(\phi_{1/2}))}, \quad (2)$$

I_N is the maximum luminous intensity in the axial direction, ϕ is the angle of irradiance and m is the order derived from a Lambertian pattern. For the proposed system, the commercial white LEDs were designed for illumination purposes, exhibiting a wide half intensity angle ($\phi_{1/2}$) of 60° . Thus, the Lambertian order m is 1. Friis' transmission equation is frequently used to calculate the maximum range by which a wireless link can operate. The coverage map is obtained by calculating the link budget from the Friis Transmission Equation [12]. The Friis transmission equation relates the received power (P_R) to the transmitted power (P_E), path loss distance (L_R), and gains from the emitter (G_E) and receiver (G_R) in a free-space communication link.

$$P_R [\text{dBm}] = P_E [\text{dBm}] + G_E [\text{dB}] + G_R [\text{dB}] - L_R [\text{dB}] \quad (3)$$

Taking into account Fig. 1b, the path loss distance and the emitter gain will be given by:

$$L_R [\text{dB}] = 22 + 20 \ln \frac{d}{\lambda}, \quad (4)$$

$$G_E [\text{dB}] = \frac{(m+1)A}{2\pi d_{E-R}^2} I(\phi) \cos(\theta) \quad (5)$$

With A de area of the photodetector and d_{E-R} the distance between each transmitter and every point on the receiver plane. Due to their filtering properties of the receptors the gains are strongly dependent on the wavelength of the pulsed LEDs. Gains (G_R) of 5, 4, 1.7 and 0.8 were used, respectively, for the R, G, B and V LEDs. I_N of 730 mcd, 650 mcd, 800 mcd and 900 mcd were considered. Taking into account Equations 1-5, the coverage map for a square unit cell is displayed in Fig. 1a. All the values were converted to decibel (dB).

To gather information from multiple transmitters, the receiver must strategically position itself to ensure the overlapping of circles corresponding to the range of each transmitter. This configuration produces a multiplexed (MUX) signal serving both as a positioning system and a data transmitter. The

selection of grid sizes is designed to prevent interference in the receiver from neighboring grid points. Figs. 1a highlight the nine potential overlaps (#1-#9), referred to as fingerprint regions, and various receiver orientations (2-9 steering angles; δ) within the unit square cell. The device captures multiple signals, computes the centroid of received coordinates, and establishes it as the reference point position. Nine reference points per unit cell offer a nuanced resolution in localizing the mobile device within each cell.

2.2. Lighting Plan layout Architecture and Geolocation

In VLC geotracking, geographic coordinates are generated, but the feature's usefulness is enhanced by using them to determine a meaningful location, to guide the user through an unfamiliar building, or to lead him to his desired meeting destination. To accomplish this, VLC uses cells for positioning and a CM (Central Manager) to keep track of everything and generate the optimal route.

Building a geometry model of buildings' interiors is complex. Indoor VLC cell design is especially important since, being man-made, buildings such as these commonly follow basic shapes (squares, equilateral triangles/regular hexagons). A square lattice topology was considered for each level. A user navigates from outdoor to indoor. This topology is represented using x , y and z axes to simplify both the figure comprehension and the distance between any pair of nodes. Each room/crossing/exit represents a node, and a path as the links between nodes. In Fig. 2a the 3D building model is depicted. The user positions can be represented as $P(x, y, z)$ by providing the horizontal positions (x, y) and the correct floor number z . The ground floor is level 0 and the user can go both below ($z < 0$) and above ($z > 0$) from there. In this study, the 3D model generation is based on footprints of a multi-level building that are collected from available sources (luminaires), and are displayed on the user receiver for user orientation. It is a requirement that the destination can be targeted by user request to the CM and that floor changes are notified. Each unit cell can be referred as $C_{i,j,k}$ where i, j, k are the x, y position in the square unit cell of the top left node.

In VLC geotracking, geographic coordinates are generated to provide location information. However, the usefulness of this feature is further enhanced by using these coordinates to determine meaningful locations within a building and guide users through unfamiliar spaces or towards specific destinations, such as meeting rooms. To facilitate this process, VLC employs cells for positioning and a Central Manager (CM) that oversees and manages the entire system, including generating optimal routes. Introducing a paradigm-shifting concept, a mesh cellular hybrid structure is unveiled, offering an approach to network

architecture. This groundbreaking framework takes shape in the form of Fig. 2b, where the components and their interactions are vividly portrayed.

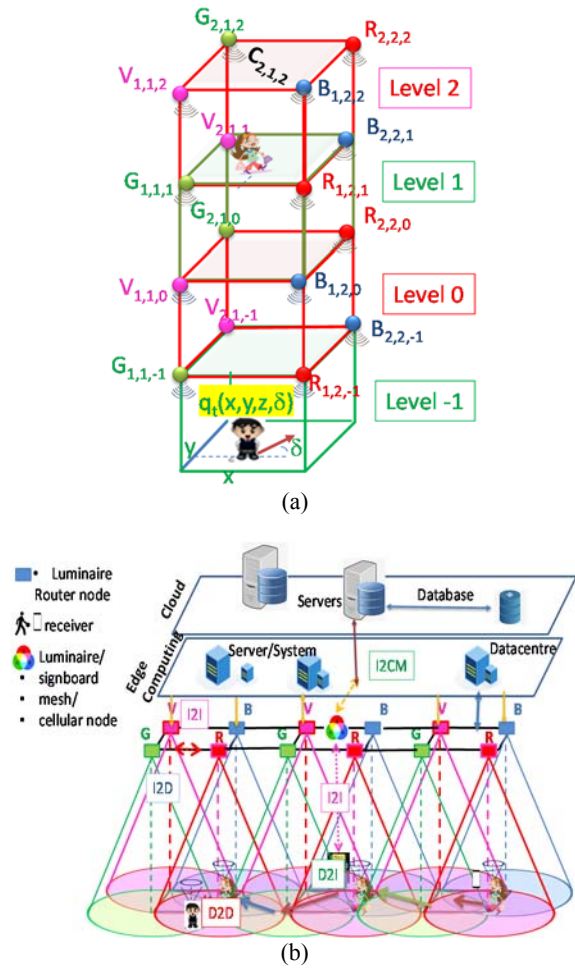


Fig. 2. a) Lighting plan; b) Mesh and cellular hybrid architecture.

In addition to the establishment of secure pathways, the mesh network excels at enabling peer-to-peer communication, commonly known as I2I interactions. This architecture is designed to foster direct information exchange among devices, a process that assumes significance in a data-driven environment. The heart of this operation lies in the ability of each WLED (White Light Emitting Diode) to emit a unique Visible Light Communication (VLC) signal, essentially acting as a beacon of identification. Employing this beacon, the optical receiver adeptly calculates the user's trajectory, employing a specialized position algorithm. This calculated indoor route, denoted as $q(x, y, z, \delta, t)$, encapsulates critical spatial and temporal information, offering users insight into their movement within the indoor environment. A user moves from outdoor to indoor and requests assistance in finding the right track (D2I). They can customize their points of interest for wayfinding services. The requested information (I2D) is sent by the emitters, at the ceiling, to its receiver.

This architecture serves two purposes: enabling edge computing and device-to-cloud communication, and enabling peer-to-peer communication for information exchange. The culmination of this intricate network architecture is marked by the role of ceiling luminaires, which assume the mantle of routers or mesh/cellular nodes. Functioning as central hubs within this ecosystem, they engage in the vital task of disseminating messages (I2D) that encapsulate the calculated indoor route. Through their orchestrated efforts, users are provided with a tangible representation of their indoor trajectory, a testament to the architecture's capability to transform data into actionable insights.

3. Cooperative Guidance System

3.1. Communication Protocol, Coding and Decoding Techniques

In the process of encoding the information, a modulation scheme known as On-Off Keying (OOK) was employed. This approach involves the toggling of the signal between two distinct states, representing binary values. Furthermore, the transmission was executed synchronously, adhering to a 64-bit data frame structure. This frame is partitioned into three primary segments: Sync, Navigation Data, and Payload. This breakdown is visually represented at the upper section of Fig. 4, and its essence is succinctly captured in the summarized form presented in Table 1.

Table 1. Frame structure.

Header	Navigation Data						Payload
Sync	x	y	z	pin ₁	pin ₂	δ	Wayfinding data
5 bits (10101)	24 bits (4 bits per field)						34 bits (.....)

Frame length = 64 bits

The header block stands as a synchronization mechanism, encompassing the bit sequence [10101]. This initial segment holds high importance, as it serves as a consistent marker repeated within each data frame. This repetition enables the receiver to accurately pinpoint the commencement of every frame. To achieve this, a standardized header bit sequence, specifically [10101], is concurrently applied to all emitters. This sequence is enacted in an alternating fashion between "on" and "off" states [10101].

Moving on to the second block, it accommodates the Identification (ID) data. This ID comprises 4+4+4 bits and conveys the geolocation information (x, y, z coordinates) of the emitters within the array. To encode these IDs, a 4-bit binary representation is adopted for decimal numbers. Notably, the z coordinate accounts for the floor number, which can be either positive or negative. To address this, the

initial bit is employed to signify the sign of the floor number ("0" for positive, "1" for negative), with the remaining three bits encapsulating the numerical value of the coordinate.

In scenarios requiring bidirectional communication, user registration is necessitated. This process involves selecting a username (pin₁) comprising four decimal numbers, with each number correspondingly linked to an RGBV channel. Additionally, should buddy friend services be sought, a 4-binary code for the meeting (pin₂) must be provided.

The last segment, termed the δ block (steering angle δ), constitutes a 4-bit sequence. This component completes the user's pose within the time frame $q(x, y, \delta, t)$. This pose is augmented with steering angle information, encompassing eight possible angles along the cardinal points. The significance of these angles, guiding the trajectory from a start point to the subsequent destination.

The codes assigned to both pin₂ and δ remain consistent across all channels. In scenarios where wayfinding services are unnecessary, these final three blocks assume a value of zero, thus furnishing the user solely with their own location information.

The third and concluding block is aptly labeled the "payload." This segment pertains to a sequence of bits that doesn't directly contribute to the navigation service. It encompasses miscellaneous data and concludes with a stop bit. To decode the information received via the photocurrent signal as captured by the photodetector, a crucial step is undertaken. This process relies on a calibration curve that has been pre-established to facilitate this mapping [10]. The calibration curve represents a sequence of bits meticulously designed to correspond to each conceivable decoding level. In essence, this calibration curve serves as a guide, aiding in the establishment of associations between photocurrent thresholds and specific bit sequences. In Fig. 3 a MUX/DEMUX signals of the calibrated cell is presented. In the same frame of time a random signal (Payload) is superimposed.

This calibration curve leverages 16 distinct photocurrent thresholds. These thresholds correspond to bit sequences meticulously engineered to cover all sixteen permutations achievable from the four RGBV input channels (24 combinations). The brilliance of this approach lies in its simplicity: by juxtaposing the calibrated levels (d_0 - d_{15}) with the assigned four-digit binary codes for each level, the decoding process becomes transparent and straightforward. This direct comparison illuminates the decoding pathway, rendering the message intelligible.

At the receiver end of the communication link, decoding occurs to separate and retrieve the encoded data coming from the emitters, which is crucial to determine the location and pose of the receiver relative to the lighting/communication infrastructure. In Fig. 3b two MUX signals received by user "7261" are displayed. On the top the decoded signals are shown.

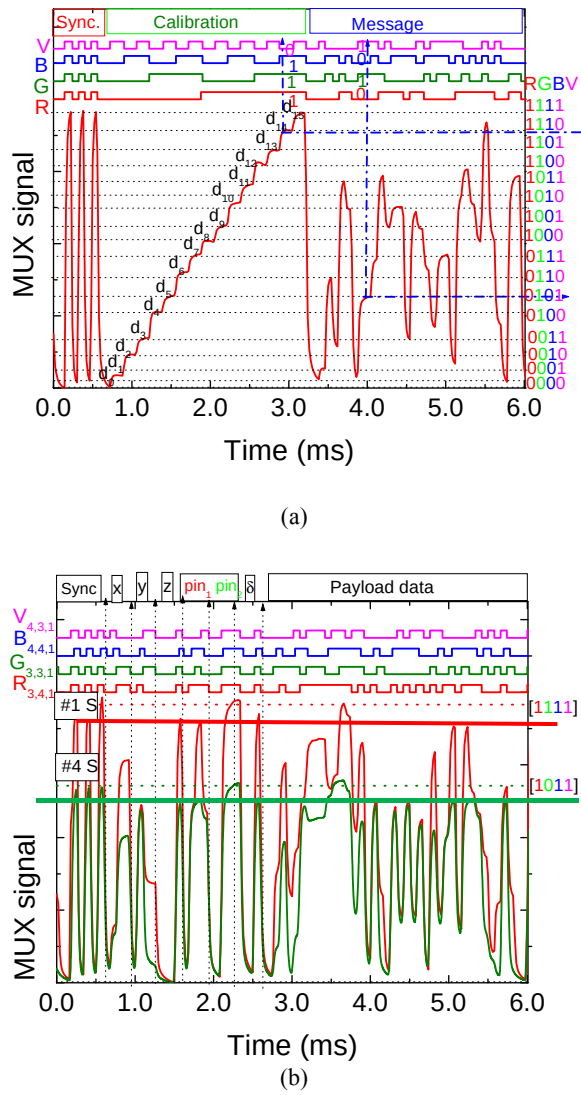


Fig. 3. a) MUX/DEMUX signals of the calibrated cell. In the same frame of time a random signal (Message) is superimposed. b) MUX signals. On the top the transmitted channels packets are decoded [R, G, B, V].

In Fig. 4 the MUX received signal and the decoding information that allows the VLC geotracking and navigation in successive instants (t_0 , t_1 , t_2) from user “7261” guiding him along his track is exemplified. The visualized cells, paths and the reference points (footprints) are also shown as inserts.

Here, the MUX received signal and the decoding information that allows the VLC geotracking and guidance in successive instants (t_0 , t_1 , t_2) from user “7261” guiding him along his track is exemplified. The visualized cells, paths, and the footprints are also shown as inserts. Data shows that at t_0 the network location of the received signals is $R_{3,2,1}$, $G_{3,1,1}$, $B_{4,2,1}$ and $V_{4,1,1}$, at t_1 the user receives the signal only from the $R_{3,2,1}$, $B_{4,2,1}$ node and at t_2 he was moved to the next cell since the node $G_{3,1,1}$ was added at the receiver. Hence, the mobile user “7261” begins his route into position #1 (t_0) and wants to be directed to his goal position, in the next cell (# 9). During the route the navigator is guided to E (code 3) and, at t_1 , steers to

SE (code 2), cross footprint #2 (t_3) and arrives to #9. The ceiling lamps (landmarks) spread over all the building and act as edge/fog nodes in the network, providing well-structured paths that maintain a navigator’s orientation with respect to both the next landmark along the path and the distance to the eventual destination.

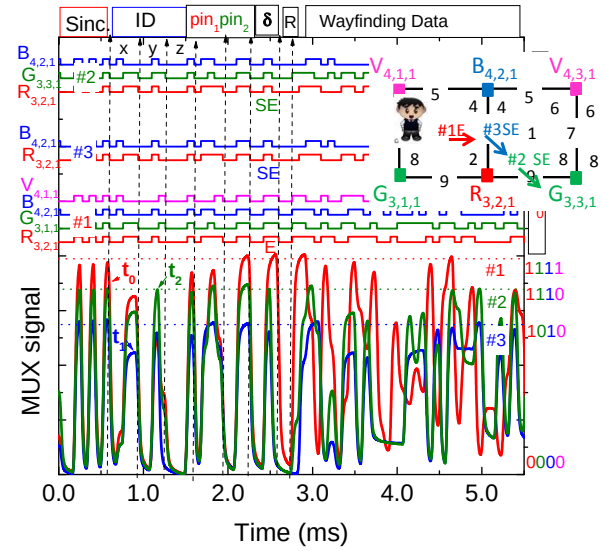


Fig. 4. Fine-grained indoor localization and navigation in successive instants. On the top the transmitted channels packets are decoded [R, G, B, V].

3.2. Multi-person Cooperative Localization and Guidance Services

In Fig. 5 the MUX synchronized signals received by two users that have requested guidance services, at different times, are displayed. In the top of the figure, the decoded information is shown and the simulated scenario is inserted to guide the eyes. At the right hand the request/response information is inserted.

We have assumed that a user located at $C_{2,3,-1}$, arrived first (t_1), auto-identified as ($q_i(t_1)$, $i = "7261"$), and informed the controller of his intention to find a friend for a previously scheduled meeting (code 3). A buddy list is then generated and will include all the users who have the same meeting code. User “3009” arrives later ($q_j(t_3)$), sends the alert notification ($C_{4,4,1}$, t_3) to be triggered when his friend is in his floor vicinity, level 1, identifies himself (“3009”) and uses the same code (code 3), to track the best way to his meeting. The “request” message includes, beyond synchronism, the identification of the user (“3009”), its address and orientation, $q_i(t)$, ($C_{4,4,1}$, #1W) and the help requested (Wayfinding Data). Since a meet-up between users is expected, its code was inserted before the right track request. Upon receiving this request (t_3), the buddy finder service uses the location information from both devices to determine the proximity of their owners ($q_{ij}(t_3)$) and provides the best route to the meeting, avoiding crowded areas. In the “response”,

the block CM identifies the CM [0000] and the next blocks the cell address ($C_{4,4,1}$), the user (3009) for which the message is intended and finally the requested information: meeting code 3, orientation NE (code 4) and wayfinding instructions.

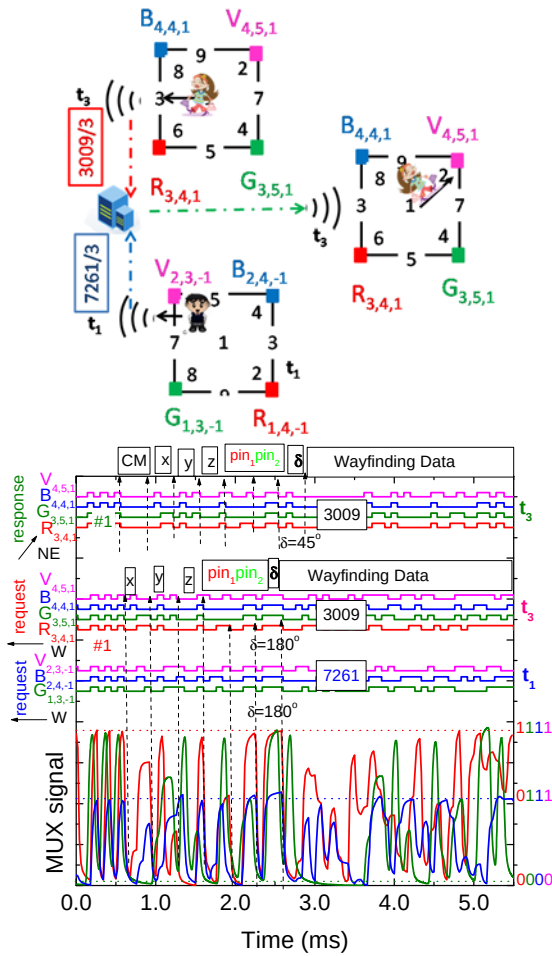


Fig. 5. MUX/DEMUX signals assigned requests from two users ("3009" and "7261") at different poses ($C_{4,4,1}$; #1W and $C_{2,3,-1}$; #6 W) and in successive instants (t_1 and t_3).

The outcomes of our study underscore the remarkable capabilities of VLC's dynamic LED-enhanced guidance system. This system not only furnishes users with precise and dependable route guidance but also empowers them to navigate effectively and engage in geotracking activities. As users traverse large building complexes, VLC technology offers a groundbreaking solution that steers them towards optimal routes while delivering continuous guidance throughout their journey.

The bidirectional communication prowess embedded within the system introduces a realm of possibilities for diverse services. Mission-critical applications can harness the inherent reliability and low-latency communication offered by the ID system. This reliability is particularly pertinent in scenarios requiring swift and trustworthy data exchange. Beyond this, the system's bidirectional

communication capacities pave the way for an array of consumer-centric services. For instance, location-based advertisements can be intelligently deployed, personalized information can be seamlessly delivered, and indoor wayfinding functionalities can be fine-tuned to heighten user experiences within the building environment.

In essence, our research not only highlights the technical capabilities of the VLC-enabled guidance system but also envisions the transformative potential it holds for users within expansive indoor spaces [13]. The system's dual nature, combining navigation and communication sets the stage for improved efficiency, enhanced experiences, and novel applications that redefine how individuals interact with and navigate through complex building structures.

4. Conclusions

This paper embarks on an exploration of the potential for Visible Light Communication (VLC) to revolutionize indoor navigation within vast building complexes. Tailored to the needs of mobile users, it introduces a novel guidance system that leverages the capabilities of VLC technology. Central to this system is a hybrid mesh cellular architecture, complemented by the establishment of an encompassing communication protocol tailored to multi-level scenarios.

The system acts as a steadfast navigational companion, seamlessly providing precise route guidance within complex indoor environments. The spectrum of functionalities includes navigation assistance, real-time route tracking, and reliable guidance for users in motion. The culmination of our experimental endeavors is reflected in global results, where the successful localization of mobile receivers coincides with the simultaneous transmission of data.

A distinctive hallmark emerges in the form of a cooperative localization mechanism. As regions within the environment become densely populated, this mechanism adeptly adapts by autonomously rescheduling localization tasks. This dynamic feature orchestrates the dissemination of guidance information and issues alerts, ensuring a responsive approach to dynamic environmental conditions.

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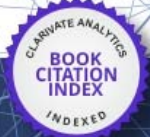
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Intrusion Detection in IoT-based Cyber-physical System Using Machine Learning

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Abstract: The use of Internet of Things (IoT) devices is a result of the massive number of messages carried through the internet. One of the most serious IoT threats is the botnet attack, which aims to commit legitimate, profitable, and effective cybercrimes. Because of the ramifications of hostile acts in computing, communication, and cyber-physical systems (CPS), researchers are encouraged to develop effective Intrusion Detection Systems (IDSs). Intelligent-powered intrusion detection solutions ideal for deployment in IoT-based cyber-physical settings are created using cutting-edge learning algorithms. In this study, three machine learning (ML) approaches are employed to develop a system that recognizes legal or malicious communication in linked computer networks. The results showed that random forest (RF) fared the best, with a coefficient of determination (R^2) of 0.9965 and error scores of 0.0015 for root mean square error (RMSE), 0.0522 for mean absolute error (MAE), and 0.0872 for mean absolute percentage error (MAPE). Despite the models achieved significant results, it was suggested that RF be used when detecting legal or malicious networks in IoT-connected computer networks. This study is crucial for making informed decisions that will lead to long-term growth in industrial and educational networks.

Keywords: Machine learning, IoT, CPS, Intrusion detection, Botnet detection, Network traffic.

1. Introduction

Cyber Physical Systems (CPS) are a symbiotic combination of computing, networking, and physical processes. CPS simulates several systems, including intelligent critical infrastructures [1]. Indeed, the widespread incorporation of CPS into critical

infrastructures has expanded their importance in ensuring economic progress, and as a result, their security and resilience have become critical in many facets of modern life. Researchers and developers established a way to achieve Industry 4.0 goals by merging machine learning (ML) technologies with industrial processes that contain intelligence [2]. The

Internet of Things (IoT) is a network of millions of physical items that connect to the Internet and perform activities automatically with little human interaction [3]. The next part of information security that we will look at is the use of automated reasoning. They have demonstrated their devotion since artificial intelligence guesses such as machine learning and deep learning offer significant potential to provide services to the IoT with their security challenges and criticality while handling heterogeneous information.

The IoT technologies and their integration with CPS enable better monitoring, control, and administration of these systems [4]. However, due to the nature of integrated IoT devices, such systems are becoming increasingly prone to component failures as well as security breaches [5], because the underlying communication protocols used may introduce new vulnerabilities into the system. To secure network resources in a conventional cyber physical system, firewalls and intrusion detection systems (IDSs) are installed as layers [6], with the firewall serving as the first layer of infrastructure and the IDS serving as the second layer of defense. An intrusion detection system (IDS) examines, manages, analyzes, and reports on any unusual events in the system and network activity [7].

Criminals may consider blacking out a business by assaulting it through a connected power meter situated within the business. They may even carry out larger attacks, such as forcing a power plant to shut down via its computer system, resulting in a total blackout. Some assaults use linked gadgets to gain access to bigger networks, such as the Internet. A connected object added to a secure infrastructure can create a new attack surface. The linked object can act as a relay for a large-scale attack. There are a lot of security breaches that have been witnessed since computing devices are interconnected for information sharing, and the Internet of things is amongst them. The first Mirai attack was encountered on Sep 2016 on the Brain Krebs website (A well-known security blogger) [8]. The second Mirai attack was encountered on Oct 2016 on Dyn (a DNS service provider) [9]. This DDoS attack made the internet service not available for its customers for several hours. All of these reports indicate that botnet attacks are a significant source of assault in IoT devices. Strategies for early detection are critical. Because new types of botnet attacks emerge every day, using a deep learning or machine learning technique to detect the botnet is critical. Deep learning and machine learning methods are critical for detecting zero-day botnet assaults. There are two methods for detecting IoT botnets. There are two types of hosts: host-based and network-based. Host-based detection on devices can be implemented by analyzing system logs and monitoring system calls. Implementing host-based security solutions on IoT devices is difficult due to their small size and limited resources.

Network-based detection can be implemented by analyzing network flow statistics, which include details such as source and destination IP addresses,

port numbers, protocols used, session duration, amount of data exchanged, number of packets sent, number of bytes sent, connection type, and so on. Because bots' initial sessions are brief while attempting to establish a connection, network flow-based botnet detection can be effective. The sessions will be lengthy after the link is established.

By examining channel characteristics in a computer networked system using distinct machine learning models, this study examines how to discern component failures (which affect typical network behavior) from network assaults.

The following are the primary contributions of this study, as adopted from [10, 11]:

1. This study presents an overall machine learning (ML) framework that makes use of data collected from computer networked Internet of Things (IoT) devices;
2. To evaluate the proposed framework for a number of different classification methods, the study employs both a simulation framework and a real-time testbed;
3. To assess the performance of the ML classifiers used in this study, four conventional performance evaluation criteria are used.
4. This study provides cutting-edge contemporary performance evaluation criteria for assessing the performance of machine learning algorithms.

The remainder of the article is organized as follows. Section 2 undertook a thorough examination of recent works in the literature arena. The methods used is described in Section 3. Section 4 explains the outcome and results of the proposed detection method, and Section 5 concludes and provides further study.

2. Related Works

A lot of researchers have conducted experiments to evaluate the resilience of CPS systems in IoT devices using ML models. To begin with, Khan et al. [12] proposed an innovative and safe architecture with a standardized process hierarchy/lifecycle for dispersed small and medium sized enterprises (SMEs) based on collaborative blockchain, internet of things (IoT), and artificial intelligence (AI) with machine learning (ML) techniques. They designed "BSMEs," a blockchain with an IoT enabled permissionless network topology that gives solutions to cross chain platforms. The B-SMEs handle the registration of participating SMEs, day-to-day information administration and exchange between nodes, and analysis of partnership exchange related transaction data before they are recorded on the blockchain immutable storage. In the IoT, Al-Wesabi et al. [13] developed a Pelican Optimization Algorithm with Federated Learning Driven Attack Detection and Classification (POAFL-DDC). For IoT threat detection, the POAFL-DDC approach used decentralized on-device data. Another study by [14] proposed a technique for identifying network anomalies in IoT devices in order to improve device security. The IoT Botnet dataset

was used in the study, and K-fold cross-validation tests were used to validate the values of assessment metrics.

Last but not least, Alghamdi and Bellaiche [15] provided a multi-pronged classification strategy for a deep ensemble-based intrusion detection system (IDS) employing Lambda architecture. To distinguish between malicious and benign traffic, binary classification used Long Short Term Memory (LSTM), whereas multi-class classification employs an ensemble of LSTM, Convolutional Neural Network, and Artificial Neural Network classifiers to detect the kind of attack.

3. Materials and Methods

This section presents the experimental procedure and the dataset utilized to train the machine learning classifiers. Additionally, this section presents the various evaluation metrics that were employed to evaluate the machine learning models.

3.1. Data Collection

It is difficult to find an adequately tagged dataset for botnet identification. This study is based on a publicly available dataset from the FigShare data repository, which may be downloaded at <https://doi.org/10.6084/m9.figshare.21769658.v1> (accessed on July 1, 2023). The dataset has already been labeled and is being analyzed for botnet identification. The data provided are used as a standard in the present study.

3.2. Data Preprocessing

The dataset was preprocessed in order to transform raw data into useful information for machine learning algorithms to grasp [16]. It is claimed that the data is generally incomplete and rife with inaccuracies [17]. Handling null or missing values, label encoding, and feature selection are all processes in the preprocessing stage.

3.3. The Data Division

The data was separated into training (70 %) and testing (30 %) sets. These are hyperparameters whose values govern the learning process and determine the model parameters that a learning algorithm learns [18]. The testing dataset aids in evaluating the models' performance.

3.4. The Machine Learning Classifiers

This study makes use of three conventional machine learning classifiers: RF, SVM, and NB. To create predictions or classifications, RF employs an

ensemble of many decision trees. The random forest technique produces a more accurate result by mixing the outputs of various trees [19]. The SVM algorithm's purpose is to find the optimum line or decision boundary for categorizing n-dimensional space so that we may simply place fresh data points in the proper category in the future. A hyperplane is the optimal choice boundary [20]. Additionally, NB is a probabilistic classifier, which means it predicts based on an object's likelihood [21]. The developed algorithms can determine whether a network is real or botnet traffic to assist enterprises, government, and organizations in making educated judgments.

3.5. Performance Evaluation Measures

In the current study, the root mean squared error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and coefficient of determination (R^2) were employed to assess the performance of the machine learning models. The greater the R^2 , as it approaches 1, the better the accuracies and the lower the error scores, and hence the better the model performance. Equations 1, 2, 3, and 4 denote the RMSE, MAE, MAPE, and R^2 , respectively.

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(y_{observed} - \hat{y}_{predicted})^2}{n}}, \quad (1)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_{observed} - \hat{y}_{predicted}|, \quad (2)$$

$$MMAPE = \frac{100\%}{n} \sum_{k=1}^n \left| \frac{y_{observed} - \hat{y}_{predicted}}{y_{observed}} \right|, \quad (3)$$

$$R^2 = \left(\frac{\sum_{i=1}^n (y_{observed} - y_{average})(\hat{y}_{predicted} - \hat{y}_{average})}{\sqrt{\sum_{i=1}^n (y_{observed} - y_{average})^2 \sum_{i=1}^n (\hat{y}_{predicted} - \hat{y}_{average})^2}} \right)^2, \quad (4)$$

where $y_{observed}$ represents the observed values, $\hat{y}_{predicted}$ is the predicted values, n is the number of samples, $y_{average}$ and $\hat{y}_{average}$ represent the average observed and predicted values, respectively.

3.6. The Proposed Architecture

The planned architecture for the study is depicted in Fig. 1. To train the dataset, the proposed machine learning models, which included the random forest (RF), support vector machine (SVM), and naive bayes models, were employed. The results reflect either genuine or botnet traffic. This results in a system driven by artificial intelligence (AI) that can detect it in real-time behavioral analysis, block it, and put an end to any botnet activity.

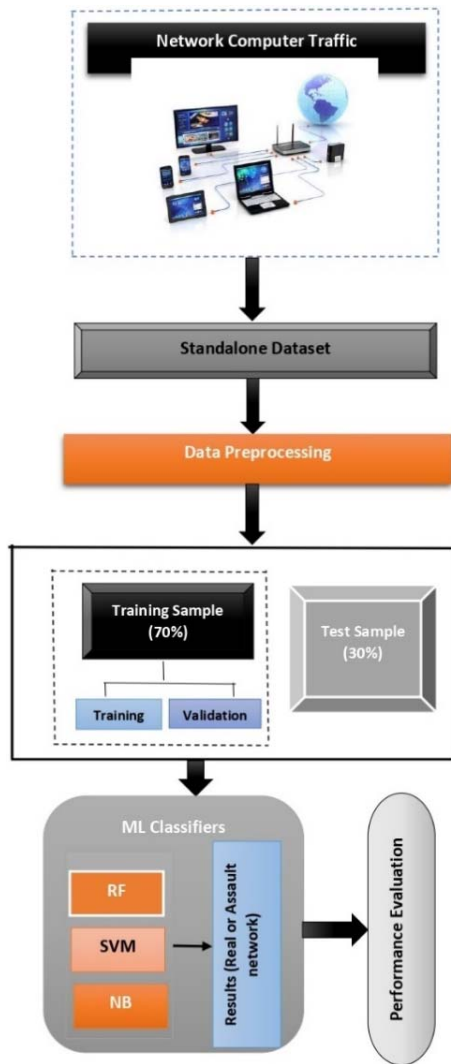


Fig. 1. The proposed architecture of the study.

4. Experimental Results and Discussion

This section presents the results gained from the ML algorithms employed for the present study.

4.1. Experimental Setup and Requirements

The proposed methodology was implemented using the Google Colab platform with Python software on a personal computer. Python is a high-level, general-purpose programming language that is free source. Because of its code readability philosophy, efficient code, easy communication features, and ease of learning, it has been the favored programming language for the majority of data scientists. Python has a vibrant scientific library as well as a number of wonderful environments, including Spyder and Jupyter Notebook. Python Matplotlib is a robust 2D graphic package that helps machine learning researchers plot graphs. We chose Python languages for our machine learning experiment because of these benefits. Furthermore, Scikit-Learn, a public and

open-source ML library for Python. It is a rapid and simple data mining and analysis tool. Scikit-learn includes supervised and unsupervised learning algorithm implementations. In addition to classification, regression, and clustering techniques, this package offers features for model selection, dimensionality reduction, and data pre-processing. SciPy, which stands for Scientific Python, is a technical computation package that is built on NumPy. Because it is an open-source library, we can freely utilize it. SciPy includes modules for optimization, linear algebra, integration, interpolation, and special functions. Matplotlib, a Python charting package, and NumPy, its numerical math extension. It provides an object-oriented API for embedding charts in programs that use general-purpose GUI toolkits.

The computer contains 32 Gb of RAM and two multicore CPUs, each with 12 cores and 2.3 gigaflops of processing power. The botnet dataset samples were trained and tested in three ways. To begin, the complete sample is divided into 70 % training and 30 % testing instances.

Finally, 10-fold cross-validation was utilized to assess the performance of the proposed model. The classification R^2 , RMSE, MAE, and MAPE are used to assess performance. Finally, the proposed model is compared to current state-of-the-art IoT-based botnet detection techniques.

4.2. Performance of the ML Algorithms

Digitization has altered the way we live and conduct our daily routines. Pervasive computing in IoT health devices has changed the medical treatment landscape. The availability of the internet on little devices is establishing a regime. These tiny gadgets are limited in resources and lack adequate security procedures. The attacker faces these vulnerable devices in order to steal sensitive data. To protect these devices, security administrators deploy various procedures such as access control mechanisms, password protection, and firewalls that use cryptographic techniques to secure the network and data. These strategies, however, are insufficient. Monitoring the network for malicious activity using machine learning and deep learning algorithms is a viable approach.

The performance of various single machine learning models in the proposed architecture is shown in Table 1. Model performance differed little between the employed algorithms. According to the data, the RF had the highest performing metrics in terms of R^2 (0.9965) and the lowest error scores in all other metrics, including RMSE (0.0015), MAE (0.0522), and (0.0872).

According to Table 1, the NB obtained the second-best performing ML model. The NB had an R^2 of 0.9261, whereas the SVM had an R^2 of 0.9125. In terms of other performance categories, the NB also had the second-best error scores in terms of RMSE (0.0032), MAE (0.0625), and MAPE (0.0877).

Although all of the models earned substantial scores in all of the performance measures, the SVM performed the worst in terms of the error scores, however, with substantial accuracy. According to this study, the RF is the best ML algorithm for recognizing legitimate or malicious communication in a linked computer network.

Table 1. ML models performance and evaluation.

Model	Metrics	Results
RF	R2	0.9965
	RMSE	0.0015
	MAE	0.0522
	MAPE	0.0872
SVM	R2	0.9125
	RMSE	0.0045
	MAE	0.0721
	MAPE	0.0880
NB	R2	0.9261
	RMSE	0.0032
	MAE	0.0625
	MAPE	0.0877

The coefficient of determination (R^2) of the models used is shown in Fig. 2. This provides a clear visualization of the models' performance. It should be noted that when the coefficient of determinant (R^2) approaches 1, the models perform better. In regression analysis, the accuracy representation is the coefficient of determinant. Random forest is the top performing model, followed by naive bayes classifiers.

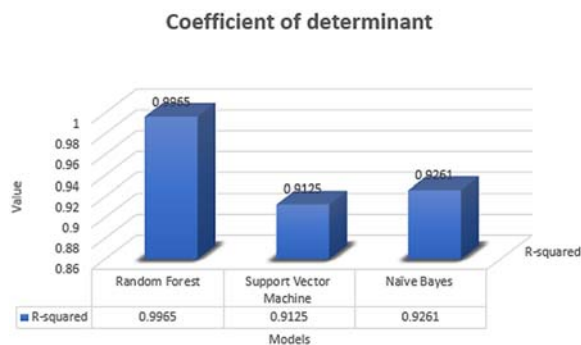


Fig. 2. R-squared representation of the ML models.

Furthermore, Fig. 3 depicts the error score performance of the models, namely, random forest, support vector machine, and naive bayes classifiers. Among the other machine learning models, the random forest achieved the best error ratings.

4.3. Comparison with State-of-the-art

Additionally, the study's findings were compared to the state-of-the-art to assess the robustness of the

models used. The RF used in the study outperformed a comparable study by Vimont et al. [22], while the NB outperformed Disha and Waheed [23] in accomplishing the same goal as this study. With considerable error scores, the proposed model beat the aforementioned studies. This study contributes a fresh method to the body of literature in the domain area. Furthermore, the study found that it is required to regularly check the functioning of connected computer networks in order to facilitate and improve communication. Computer networks are critical to modern society because they enable the transmission and sharing of information between individuals, groups, and objects. The suggested model is more adaptable and efficient than previous models due to its consistent performance across the coefficient of determination and error rate. The selection of characteristics is another factor that distinguishes the proposed model from previous detection methods. The suggested model performs better with training sets, whereas other approaches under consideration required a large number of variables for botnet detection. Furthermore, the integration of both models strengthens the detection process for both binary and multiclass attack detection scenarios.

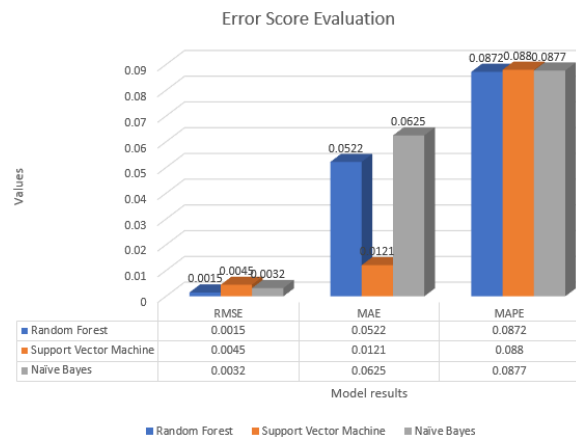


Fig. 3. Error scores of the ML classifiers.

4.4. Analysis of the 10-fold Validation

The data was randomly divided into ten blocks for 10-fold cross-validation, with one block used to train the model and the other nine blocks sent for testing. Finally, the model's performance is determined by averaging the test results from all nine blocks of samples. The k-fold cross-validation method has been proposed as a viable method for analyzing the performance of botnet detection models. Based on the results of the data distribution training outcome of the models, the 10-fold cross-validation that was used had a substantial impact on the performance of the models, thus the 70 %-30 % training and testing split. Again, the model detects all network threats, including DoS and DDoS attempts. The exact inference and results

are also revealed by the depiction of the R2 values in Fig. 2 and the error scores in Fig. 3. Though the suggested model detects several botnet attacks smoothly, with the exception of a few minor class attacks, the model's overall performance must be compared to contemporary state-of-the-art intrusion detection models, which inevitably reveals its true detection capabilities.

5. Conclusion and Future Works

Computer networks have had a huge impact on society by providing global connectivity and information exchange. The utilization of Internet of Things devices has greatly changed communication, and hence digital communication. This study demonstrated that machine learning techniques are effective in detecting actual or malicious traffic in a connected computer network. The models used in this study produced considerable results, and their influence on providing a benchmark analysis for decision making is enormous. The system achieved a performance rate of over 90 % in terms of the coefficient of determinant rates in all three machine learning models, proving it to be a better detector than other peers' botnet detection. Despite the observed performance, the proposed model has several drawbacks. One of the flaws is the lack of a feedback strategy, which might help the system to become more dynamic.

A feedback technique may enable the model to separate the compromised instances or hosts from the network, resulting in a more reliable network communication process. The system fails to detect minority class attack instances such as Heartbleed, Infiltration, and Web-SQL Injection throughout the 10-fold cross validation test and 70 %-30 % train and testing instances split test, posing a challenge to the suggested botnet identification methodologies. It was related to the minority class instances' low engagement in the training program.

The authors want to use deep learning techniques such as convolutional neural networks (CNN) and hybrid models such as random forest-convolutional neural network (RF-CNN) in the future.

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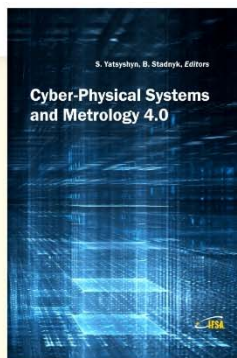
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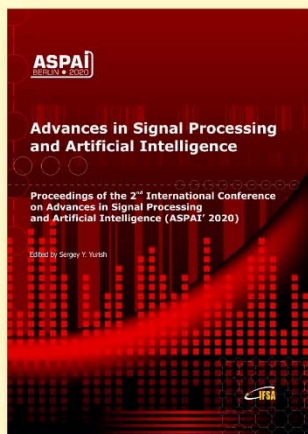


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On the Possible Method of Improving Properties of Semiconductor Lasers

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Abstract: This paper is aimed as a concise, short introduction to semiconductor lasers and a presentation of a specific method to improve optical gain. We start with the short description of lasers and semiconductor lasers, in particular. They play an important role in current technological developments. They found applications in many popular devices and communication systems, like laser printers, DVD players, optical fiber communications, to just name a few. In this paper, we outline fundamentals of semiconductor lasers and concentrate on those based on quantum wells. Properties and operating parameters of those devices can be optimized for a certain application. Here we concentrate on the influence of growth directions on optical gain. We summarized mathematical formalism used to determine band structure and gain and have conducted numerical simulations for various orientations of the crystal.

We illustrate the applicability of our formalism by presenting results (band structure and material gain) for only few high symmetry orientations of the substrate and concentrate on quantum wells fabricated from InGaAsN/GaAs. Modifications of band structure due to rotations significantly affect material gain.

Our approach can also be extended to other semiconductor materials. They can help to design lasers with improved characteristics.

Keywords: Semiconductor lasers, Band structure, Crystallographic orientation, Material gain.

1. Introduction

Generic laser consists of a resonator (cavity) typically formed by two mirrors and gain medium located between mirrors where the amplification of electromagnetic radiation (light) takes place. Such a system is an oscillator analogous to one in electronics. To form an oscillator, an amplifier (where gain is created) and feedback are needed. Feedback is provided by two mirrors which also confine light. One of the mirrors is partially transmitting which allows

light to escape from the device. In short, a laser is an oscillator analogous to an oscillator in electronics.

There must be an external energy provided into gain medium (process known as pumping). Most popular (practical) pumping mechanisms are by optical or electrical means.

In this paper we concentrate on important class of lasers, namely semiconductor lasers (SL), see [1, 2] for recent general introduction to SL. They play an important role in today's technological developments. They can be found in popular devices, like iPhones,

DVD players and laser printers. In short, semiconductor laser (name laser diode is also often used) is based on p-n junction which is combined with an optical resonator. The p-n junction forms a diode which operates in a forward direction.

2. Basic Facts of Semiconductor Lasers Based on Quantum Wells

Generally, semiconductor lasers (also known as laser diodes) can be broadly classified into two basic types: edge-emitting lasers, or surface-emitting lasers.

A typical edge-emitting laser has the longitudinal direction of the optical cavity oriented perpendicular to the flow direction of electrical current in the device.

On the other hand, in surface-emitting lasers the optical cavity is oriented along flow of electrical current and it is perpendicular to the growth direction. A popular example of the surface emitting laser is the vertical-cavity surface-emitting laser (VCSEL). In this structure the optical cavity is short, on the order of a wavelength of the light. To achieve reasonably low threshold current in such devices the mirrors must have very high reflectivity.

Three-dimensional (3D) view of a generic edge-emitting semiconductor laser (the so-called Fabry-Perot) is shown in Fig. 1.

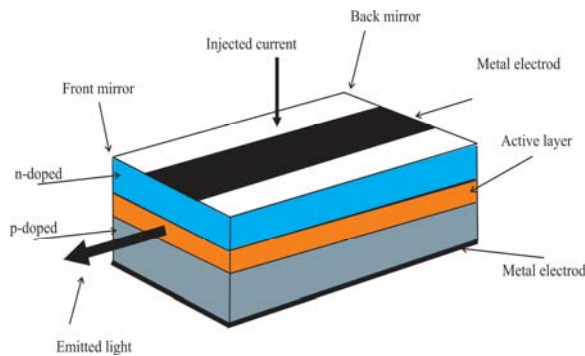


Fig. 1. Schematic of Fabry-Perot laser.

The main element of this structure is associated with the existence of the so-called Fabry-Perot resonator cavity where the optical feedback is provided by the difference in refractive indices between semiconductor structure and external environment.

It is possible to have different types of mirrors as they also provide mode selectivity. Two basic types of SL are distributed feedback (DFB) laser and distributed Bragg reflector (DBR) [3].

In DFB lasers, grating (corrugation) is produced in one of the cladding layers thus creating Bragg reflections at such periodic structure. The structure causes a wavelength sensitive feedback. It should be emphasized that the grating extends over entire laser structure. When one restricts corrugation to the mirror

regions only and leaves flat active region in the middle, then the so-called DBR structure is created, which also provides wavelength sensitive feedback.

Every laser structure consists of many layers of various materials, each playing a different role. Those layers are responsible for the efficient transport of electrons and holes from electrodes into an active region and also for confinement of carriers and photons into active region so they can strongly interact.

In semiconductor laser diodes the emission of light is due to the radiative recombination of the electron-hole pairs. Electron-hole pairs are formed by electrons from conduction band (CB) and holes from valence band (VB). Between these bands there exists the forbidden band characterized by bandgap energy.

Typical characteristic of SL is shown in Fig. 2. It shows output power vs driving electric current. The output power degrades fast with increased temperature of the sample.

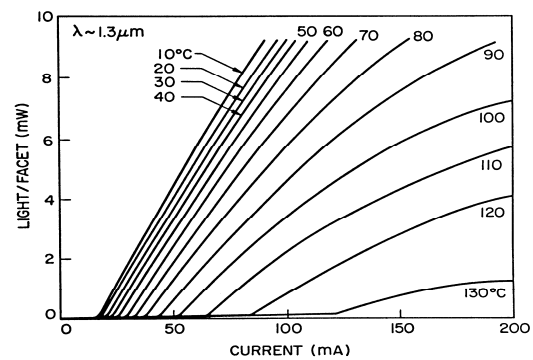


Fig. 2. Typical characteristic of SL showing output power versus current.

Modern SL structures are based on so-called quantum well which form active region and where conduction-valance band transitions are taking place, see Fig. 3.

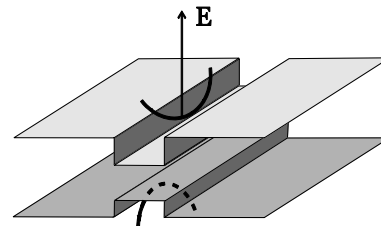


Fig. 3. Schematic of the quantum-well structure.

The structure is formed by two semiconductors with different bandgaps. They create the so-called heterostructure. Carriers (electrons and holes) can move freely within well (their dispersion relation is parabolic) but along direction perpendicular to the well their energies are quantized, see Fig. 4.

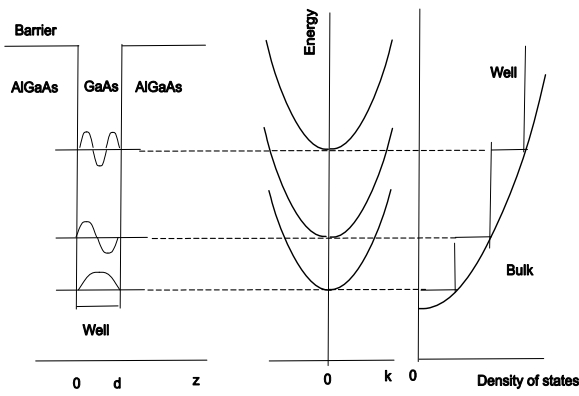


Fig. 4. Schematic of quantization of energies within the quantum-well structure.

3. Methods of Improving Properties (Characteristics) of Semiconductor Lasers

There is a long list of parameters of SL which could be optimized and improved. Over the years there were many efforts towards the improvement of their operating characteristics and also application of new materials. Various compounds and their functionalities have been analyzed in recent years. For example, applications in ultraviolet emitters were recently reviewed by Kudrawiec and Hommel [4].

In this work we briefly concentrate on high-power devices, fast devices (those which are directly modulated) and also on improving (making larger) material (optical) gain.

Fundamental and technological reasons limiting the optical power of SL were analyzed by several groups, see e.g., Tarasov [5]. The design of high-power SL discussed by Tarasov is based on separate-confinement double heterostructures (SC DHs). Often the SC DH is used to confine an electromagnetic wave by a waveguide layer which results in decrease of threshold current density due to decrease of the active region thickness. The use of a quantum-well epitaxial layer as an active region of the laser SC DH allowed one to reduce the threshold current density to 40 A/cm² [5].

Another important problem is to increase speed of directly modulated SL [6]. SL can be modulated using two methods: direct modulation or using external modulators (costly approach). Common approach is to directly modulate diode current which leads to appropriately modulated output power.

However, in this approach relaxation oscillations are created. They are characterized by a relaxation-oscillation frequency which describes rate at which energy is exchanged between photon system and carriers. Another limit is introduced by parasitics. As a result, the maximum modulation frequencies range from 1 to 70 GHz, depending on the type of laser and its packaging.

Carrier transport effects are another limiting factor for direct modulation of semiconductor lasers [7].

Optimizing transport of carriers, especially in the multiple quanta well systems results in faster devices. Based on rate equation model it was demonstrated that the tunneling injection mechanism increases the modulation bandwidth of the laser output compared to the classical injection mechanism [7].

Yet, another issue is to increase optical gain of SL. One possible method is to growth samples on rotated substrates. In the following we concentrate on this issue.

It has been known for a long time that the growth of quantum wells (QWs) at the rotated substrates (as opposed to the natural (001) direction) results in the improved properties of semiconductor lasers based on various material systems. Over the years several material systems has been analyzed, both theoretically and experimentally. For a recent summaries of various growth methods, see [8]. Typical discussed material systems were GaAs-AlGaAs and InGaAsP-GaInAs. Theoretical approaches were based on 4- band, 6-band and 8-band Hamiltonians.

On the theoretical side it was concluded that selecting proper orientation of the substrate results in lower (compared to (001) direction) threshold current [9, 10]. It was also determined that differential gain is about 1.6 times larger for the (110)-oriented 1.55 μm strained QWs than for equivalent (001)-oriented QWs [11]. It was also found that linewidth enhancement factor in strained QW laser based on In_{0.7}Ga_{0.3}As-InP is smaller for (111) growth direction than in conventional strained QW lasers on (001) substrates [12]. Typical value calculated for the (111) rotated substrate was less than 1.4, much lower than for conventional strained QW lasers on (001) substrates. In addition to the above material systems, in recent years dilute nitride semiconductors such as InGaAsN attracted wide attention. Their study is motivated by potential applications in GaAs-based laser diodes operating at 1.3 and 1.55 μm. Those material systems are modeled using 10-band Hamiltonians which are combinations of 8-band model and BAC model [13], [14]. Currently, optical and electrical properties including band structure of InGaAsN/GaAs quantum wells (QWs) are well described in the literature. Most of the reported results were focused on the (001)-oriented substrates. Some of the papers for (001) oriented QWs were published by Ng et al [15] and Gladysiewicz et al. [16].

4. Theoretical Approach

4.1. General

To describe the system (laser) we used the kp method. It is based on the following Hamiltonian

$$H = \frac{1}{2m_0} \hat{\mathbf{p}}^2 + V(\mathbf{r}) + \frac{\hbar}{4m_0^2 c^2} \hat{\boldsymbol{\sigma}} \cdot \nabla V \times \hat{\mathbf{p}} = H_0 + H_{SO}, \quad (1)$$

where H_0 is the zeroth-order term and H_{SO} describes spin-orbit interaction. The basic functions are summarized below

$$\begin{aligned}
 u_{10}(\vec{r}) &= \left| \frac{3}{2}, \frac{3}{2} \right\rangle = \frac{-1}{\sqrt{2}} |(X+iY) \uparrow\rangle \\
 u_{20}(\vec{r}) &= \left| \frac{3}{2}, \frac{1}{2} \right\rangle = \frac{-1}{\sqrt{6}} |(X+iY) \downarrow\rangle + \sqrt{\frac{2}{3}} |Z \uparrow\rangle \\
 u_{30}(\vec{r}) &= \left| \frac{3}{2}, \frac{-1}{2} \right\rangle = \frac{1}{\sqrt{6}} |(X-iY) \uparrow\rangle + \sqrt{\frac{2}{3}} |Z \downarrow\rangle \\
 u_{40}(\vec{r}) &= \left| \frac{3}{2}, \frac{-3}{2} \right\rangle = \frac{1}{\sqrt{2}} |(X-iY) \downarrow\rangle \\
 u_{50}(\vec{r}) &= \left| \frac{1}{2}, \frac{1}{2} \right\rangle = \frac{1}{\sqrt{3}} |(X+iY) \downarrow\rangle + \frac{1}{\sqrt{3}} |Z \uparrow\rangle \\
 u_{60}(\vec{r}) &= \left| \frac{1}{2}, \frac{-1}{2} \right\rangle = \frac{1}{\sqrt{3}} |(X-iY) \uparrow\rangle - \frac{1}{\sqrt{3}} |Z \downarrow\rangle
 \end{aligned} \quad (2)$$

4.2. Description of Rotations

Normally, the system is described assuming the z-axis to be perpendicular to the quantum well. In order to describe rotations of the substrate we follow method as described in [17], see Fig. 5. Below, we briefly summarize the approach.

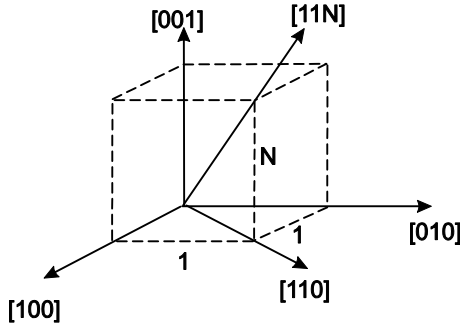


Fig. 5. Relationship of the general [11N] coordinate system to the conventional [001] crystal coordinate system.

We use the following notation for coordinate systems, see Fig. 6: the (x,y,z) is associated with the (001) oriented QW and (1,2,3) coordinate system with arbitrary rotated QW. The growth direction for (001) -oriented substrate is along z axis and along 3 axes for rotated substrate. To obtain rotated Hamiltonian from (001)-oriented Hamiltonian the following rotation matrix is used.

$$U = \begin{bmatrix} \cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \\ -\sin \phi & \cos \phi & 0 \\ \sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \end{bmatrix} \quad (3)$$

The matrix has the following properties: $U^T = U^{-1}$, $U^T U = I$ and $U_{ik} U_{jk} = \delta_{ij}$. The components of vectors and tensors transform as

$$\begin{aligned}
 k'_i &= U_{i\alpha} k_\alpha, \quad \varepsilon'_{ij} = U_{i\alpha} U_{j\beta} \varepsilon_{\alpha\beta}, \\
 C'_{ijkl} &= U_{i\alpha} U_{j\beta} U_{k\gamma} U_{l\delta} C_{\alpha\beta\gamma\delta},
 \end{aligned} \quad (4)$$

where superscripts “-1” means matrix inverse and “T” means matrix transposition. Here ϕ is the angle between x-z and 1-3 planes and θ is the angle between axis z and axis 3. Here k and k' are wave vectors and ε_{ij} and $\varepsilon'_{\alpha\beta}$ are strain tensors for (001) and arbitrary orientation, respectively. In other words, the angles θ and ϕ are Euler rotation angles about axes 2 and z respectively. The angles with respect to (001) direction for (hkl) Miller planes can be obtained by the following relations

$$\theta = \tan^{-1} \frac{\sqrt{h^2 + k^2}}{l} \quad \phi = \tan^{-1} \frac{k}{h} \quad (5)$$

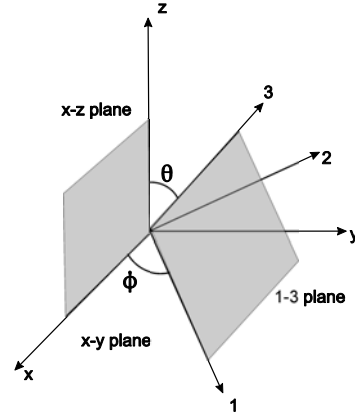


Fig. 6. General transformation for arbitrary rotation from old to new rectangular coordinate system using spherical coordinate system: Axes x, y, z transform to axes 1, 2, 3 respectively, which are perpendicular to each other; x-z and 1-3 planes are indicated.

Transformation matrix leads to the following relation

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} U \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (6)$$

The spins in the original coordinate system are assumed to be along the growth direction z. For rotated system, spins will be rotated by the rotation matrix for spins

$$M_s = \begin{bmatrix} e^{-i\frac{\phi}{2}} \cos \frac{\theta}{2} & e^{i\frac{\phi}{2}} \sin \frac{\theta}{2} \\ -e^{-i\frac{\phi}{2}} \sin \frac{\theta}{2} & e^{i\frac{\phi}{2}} \cos \frac{\theta}{2} \end{bmatrix}, \quad (7)$$

which leads to the following relation

$$\begin{bmatrix} \uparrow' \\ \downarrow' \end{bmatrix} = \begin{bmatrix} e^{-i\frac{\theta}{2}} \cos \frac{\theta}{2} & e^{i\frac{\theta}{2}} \sin \frac{\theta}{2} \\ -e^{-i\frac{\theta}{2}} \sin \frac{\theta}{2} & e^{i\frac{\theta}{2}} \cos \frac{\theta}{2} \end{bmatrix} \begin{bmatrix} \uparrow \\ \downarrow \end{bmatrix} \quad (8)$$

By combining matrices U and M_s we can relate basis functions in rotated coordinate system $[X', Y', Z']^T$ with spins $[\uparrow', \downarrow']^T$ and basis functions in original coordinate system $[X, Y, Z]^T$ with spins $[\uparrow, \downarrow]^T$. Combining matrices U and M_s , we can obtain matrix that relates $[X' \uparrow', Y' \uparrow', Z' \uparrow', X' \downarrow', Y' \downarrow', Z' \downarrow']^T$ and $[X \uparrow, Y \uparrow, Z \uparrow, X \downarrow, Y \downarrow, Z \downarrow]^T$, where superscript T means transposition. The combined matrix is obtained as a Kronecker product $\otimes$ (outer product for matrices) of matrices M_s and U .

$$M_c = M_s \otimes U \quad (9)$$

The matrix M_c leads to the following relation between basis functions

$$\begin{bmatrix} X' \uparrow' \\ Y' \uparrow' \\ Z' \uparrow' \\ X' \downarrow' \\ Y' \downarrow' \\ Z' \downarrow' \end{bmatrix} = M_c \begin{bmatrix} X \uparrow \\ Y \uparrow \\ Z \uparrow \\ X \downarrow \\ Y \downarrow \\ Z \downarrow \end{bmatrix}, \quad (10)$$

where empty space in square brackets corresponds to matrix M_c . Full form of matrix M_c was provided in [17].

4.3. The Effect of Strain

The strain effects are modeled using Bir and Pikus approach [19]. The strain tensor takes different explicit forms for various strain situations. The strain tensor components are represented by

$$\varepsilon_{xx} = \varepsilon_{yy} = \frac{a_{GaAsBi} - a_{GaAs}}{a_{GaAs}} \quad (11)$$

The form of ε_{zz} varies with orientation, due to the fact that the elastic stiffness tensor is transformed. The relevant expressions are

$$\varepsilon_{zz}^{(001)} = -2 \frac{C_{12}}{C_{11}} \varepsilon_{xx}, \quad (12)$$

$$\begin{aligned} \varepsilon_{zz}^{(110)} &= -\frac{3C_{12} + C_{11} - 2C_{44}}{C_{11} + 2C_{12} + 4C_{44}} \varepsilon_{xx}, \\ \varepsilon_{zz}^{(111)} &= -2 \frac{C_{11} + 2C_{12} - 2C_{44}}{C_{11} + 2C_{12} + 4C_{44}} \varepsilon_{xx} \end{aligned} \quad (13)$$

Other terms of the strain tensor are equal to zero. The components of Bir and Pikus strain Hamiltonian involve the following contributions (the zero terms are not listed below)

$$T_\varepsilon = \frac{P_0}{\sqrt{6}} (\varepsilon_{xx} k_1 + i \varepsilon_{yy} k_2), \quad U_\varepsilon = \frac{P_0}{\sqrt{3}} \varepsilon_{zz} k_3, \quad (14)$$

$$\begin{aligned} Q_\varepsilon^{(001)} &= -b(\varepsilon_{xx} - \varepsilon_{zz}), \\ Q_\varepsilon^{(110)} &= \left(-\frac{b + \sqrt{3}d}{4} \right) (\varepsilon_{xx} - \varepsilon_{zz}), \\ Q_\varepsilon^{(111)} &= \frac{d}{\sqrt{3}} (\varepsilon_{xx} - \varepsilon_{zz}), \end{aligned} \quad (15)$$

$$R_\varepsilon^{(110)} = \left(\frac{\sqrt{3}b - d}{4} \right) (\varepsilon_{xx} - \varepsilon_{zz}) \quad (16)$$

The strain contributions, which are independent of orientation are the following: for valence band

$$P_\varepsilon = -a_v \text{Tr}(\varepsilon), \quad (17)$$

and for conduction band

$$E_\varepsilon^{CB} = a_c \text{Tr}(\varepsilon) \quad (18)$$

4.4. 8-band Hamiltonian

In this basis the rotated Hamiltonian is

$$\begin{pmatrix} A & 0 & \sqrt{3}T & -\sqrt{2}U & T^+ & 0 & U & -\sqrt{2}T^+ \\ 0 & A & 0 & -T & -\sqrt{2}U & -\sqrt{3}T^+ & -\sqrt{2}T & -U \\ \sqrt{3}T^+ & 0 & P+Q & -S & R & 0 & -\frac{S}{\sqrt{2}} & \sqrt{2}R \\ -\sqrt{2}U & -T^+ & -S^+ & P-Q & 0 & R & -\sqrt{2}Q & \sqrt{\frac{3}{2}}S \\ T & -\sqrt{2}U & R^+ & 0 & P-Q & S & \sqrt{\frac{3}{2}}S^+ & \sqrt{2}Q \\ 0 & -\sqrt{3}T & 0 & R^+ & S^+ & P+Q & -\sqrt{2}R^+ & \frac{S^+}{\sqrt{2}} \\ U & -\sqrt{2}T^+ & -\frac{S^+}{\sqrt{2}} & -\sqrt{2}Q^+ & \sqrt{\frac{3}{2}}S & -\sqrt{2}R & P+\Delta & 0 \\ -\sqrt{2}T & -U & \sqrt{2}R^+ & \sqrt{\frac{3}{2}}S^+ & \sqrt{2}Q^+ & -\frac{S}{\sqrt{2}} & 0 & P+\Delta \end{pmatrix} \quad (19)$$

Standard definitions of terms of unrotated system are

$$\begin{aligned}
P &= \frac{\hbar^2}{2m_0} \gamma_1 (k_x^2 + k_y^2 + k_z^2) = \frac{\hbar^2}{2m_0} \gamma_1 k^2, \\
Q &= \frac{\hbar^2}{2m_0} \gamma_2 (k_x^2 + k_y^2 - 2k_z^2), \\
R &= \frac{\hbar^2}{2m_0} \left[-\sqrt{3} \gamma_2 (k_x^2 - k_y^2) + i2\sqrt{3} \gamma_3 k_x k_y \right], \\
S &= \frac{\hbar^2}{m_0} \gamma_3 \sqrt{3} (k_x - ik_y) k_z
\end{aligned} \quad (20)$$

Matrix elements related to conduction band interactions are

$$\langle S | H | S \rangle = E_c + A' k^2 = A \quad (21)$$

Matrix elements for some particular orientations (001), (110), (111) are

$$A^{(001)} = A^{(110)} = A^{(111)} = A^{(112)} = A \quad (22)$$

The values of matrix elements Q , R and S depend on orientation. For selected orientations they are

$$Q^{(001)} = -\frac{\hbar^2}{2m_0} \gamma_2 (k_1^2 + k_2^2 - 2k_3^2) \quad (23)$$

$$\begin{aligned}
Q^{(110)} &= -\frac{\hbar^2}{4m_0} \left(\gamma_2 (2k_1^2 - k_2^2 - k_3^2) - 3\gamma_3 (k_2^2 - k_3^2) \right), \\
Q^{(111)} &= -\frac{\hbar^2}{2m_0} \gamma_3 (k_1^2 + k_2^2 - 2k_3^2), \\
R^{(001)} &= \frac{\hbar^2}{2m_0} \sqrt{3} \left(\gamma_3 (k_1^2 - k_2^2) - i2\gamma_2 k_1 k_2 \right), \\
R^{(110)} &= \frac{\hbar^2}{4m_0} \sqrt{3} \left(\gamma_2 (2k_1^2 - k_2^2 - k_3^2) - \gamma_3 [(k_2^2 - k_3^2) + i4k_1 k_2] \right), \\
R^{(111)} &= \frac{\hbar^2}{6m_0} \left(\sqrt{3} (\gamma_2 + 2\gamma_3) (k_1 - ik_2)^2 - 2\sqrt{6} (\gamma_2 - \gamma_3) (k_1 + ik_2) k_3 \right), \\
S^{(001)} &= \frac{\hbar^2}{m_0} \sqrt{\frac{3}{2}} \gamma_3 (k_1 - ik_2) k_3, \\
S^{(110)} &= \frac{\hbar^2}{m_0} \sqrt{\frac{3}{2}} (\gamma_3 k_1 k_3 - i\gamma_2 k_2 k_3), \\
S^{(111)} &= -\frac{\hbar^2}{6m_0} \left(\sqrt{3} (\gamma_2 - \gamma_3) (k_1 + ik_2)^2 - \sqrt{6} (2\gamma_2 + \gamma_3) (k_1 - ik_2) k_3 \right)
\end{aligned} \quad (24)$$

5. Numerical Approach

We start by expanding all position dependent terms in the Hamiltonian in the plane wave basis as

$$A(z) = \frac{1}{\sqrt{L}} \sum_m A_m e^{iK_m z}, \quad K_n = \frac{n\pi}{L}, \quad (25)$$

By multiplying from the left by

$$A(z) = \frac{1}{\sqrt{L}} \sum_m A_m e^{iK_m z}, \quad K_n = \frac{n\pi}{L}, \quad (26)$$

we arrive at an effective mass equation in plane wave basis of the form

$$[H]_{m',m} [f_{\alpha,m',(n)}] = E_{(n)} [f_{\alpha,m',(n)}] \quad (27)$$

Here, square brackets denote matrix and arrays in plane-wave basis. The n -th envelope eigenfunction is

$$F_n(z, k_p) = \frac{1}{\sqrt{L}} \sum_{\alpha,m} f_{\alpha,m,(n)}(k_p) e^{iK_m z} \quad (28)$$

6. Gain

In Fig. 7 we illustrate the origin of gain in an active system. External pump (in the case of semiconductor lasers the role is played by electric current) provides energy which is responsible for growth of photons.

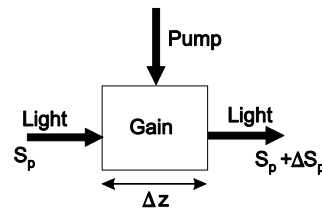


Fig. 7. Illustration of gain process.

Material gain was determined using a conventional method [20] based on the relaxation time approximation convoluted with a Lorentzian function with broadening time (0.1ps). In this approximation, the transverse electric (TE) gain is given by

$$g_{\beta}^{TE}(\omega) = C_0 \beta^{-1} \sum_{n_c, n_v} \int dk [f_{n_c}(k) - f_{n_v}(k)] \times \sum_i |\langle \psi_{n_c} | \varepsilon \cdot p_{\alpha} | \psi_{n_v} \rangle|^2 L(n_c, n_v, k), \quad (29)$$

where $C_0 = q^2 / (m_0^2 \omega \tau c \epsilon_0)$, q is elementary charge, m_0 is bare mass of an electron, ω is angular frequency, τ is a time constant, c speed of light, ϵ_0 dielectric constant and β propagation constant of the TE mode. Index i labels the heavy and light hole subbands, f_{nc} and f_{nv} are Fermi-Dirac distributions for n -th electron and hole subbands in the QW, respectively. They are given below

$$f_c(E_c(k), E_c^F) = \left(1 + \exp\left(\frac{E_c(k) - E_c^F}{k_B T}\right) \right)^{-1}, \quad (30)$$

$$f_v(E_v(k), E_v^F) = \left(1 + \exp\left(\frac{E_v(k) - E_v^F}{k_B T}\right) \right)^{-1}$$

where k_B is the Boltzmann's constant and T is the absolute temperature.

Various transitions between conduction band and valence bands which contribute to gain, Eq. (29) are illustrated in Fig. 8.

The squared optical transition matrix elements of TE mode which measure the transition between the hole subbands and the electron subbands are

$$|\langle \psi_{nc} | \epsilon \cdot p_\alpha | \psi_{nv} \rangle|^2 = (M_{ci}^{TE})^2 |I_{nv,i}^{nc}(k)|^2, \quad (31)$$

$$\alpha = x, y, z$$

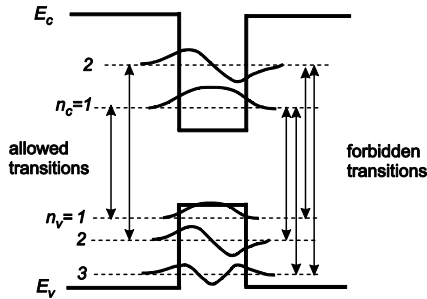


Fig. 8. Various transitions inside quantum well which contribute to material gain.

The overlap integral is defined as

$$|I_{nv,i}^{nc}(k)| = \int \psi_{nc}(k) \psi_{nv}(k) dz \quad (32)$$

The element M_{ci}^{TE} is evaluated for TE modes within dipole approximation. The broadening function is

$$L(n_c, n_v, k) = \frac{1}{\pi} \frac{\hbar / \tau}{(E_{eh} - E)^2 + (\hbar / \tau)^2} \quad (33)$$

Carrier densities in conduction (N) and valence (P) band are obtained as

$$N = \sum_{n_c} \int_0^{k_{\max}} \rho(k) f_c(E_{n_c}(k), E_{CB}^F) dk, \quad (34)$$

$$P = \sum_{n_v} \int_0^{k_{\max}} \rho(k) [1 - f_v(E_{n_v}(k), E_{VB}^F)] dk \quad (35)$$

Material gain was evaluated for several carrier densities. For each density we have determined the quasi-Fermi levels E_{CB}^F and E_{VB}^F for the CB and VB, respectively. The carrier density in a given band of the QW is defined by integration of the product of density of states, $\rho(k, z)$:

$$Q(k, z) = \frac{kT}{\pi \hbar^2} \sum_{m,s,\alpha} |I_{nv,i}^{nc}(k)|^2 \frac{1}{1 + \exp(\frac{E_{c,f}^F}{kT})}, \quad (36)$$

and occupation probability of carriers (i.e., the Fermi-Dirac distribution) over the entire band. For non-parabolic bands, the integration is carried out in k space with the density of states determined from kp calculations. $k_{\max}$ is the integration limit determined by the convergence of integrals used to determine N and P .

7. Results

Calculations were performed for 7 nm quantum wells made of $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}_{0.973}\text{N}_{0.027}/\text{GaAs}$. Our numerical approach was described in an earlier Section. All parameters which depend on compositions were obtained using linear interpolation.

Some of the results are summarized in Figs. 9 and 10. All results are compared with a standard direction (001). In Fig. 9 we show band dispersion, i.e., dependence of energy vs k -vector.

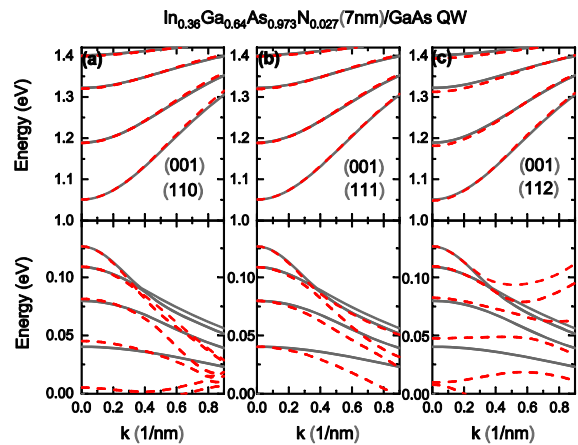


Fig. 9. Band structure calculated for $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}_{0.973}\text{N}_{0.027}/\text{GaAs}$ QW grown on directions: (a) (001) gray line, (110) red line, (b) (001) gray line, (111) red line, (c) (001) gray line, (112) red line.

One can observe that results of the band structure calculations show significant differences for substrates oriented along (110), (111) and (112) with respect to (001) direction. Differences in the band

structure are particularly significant for the valence band. One can notice that for each direction effective masses of holes differ from the (001) direction. The changes in the conduction band for different directions are relatively small.

Some of the results of the material gain spectra are shown in Fig. 10. The calculations were performed for carrier concentrations ranging from $1 \times 10^{18} \text{ cm}^{-3}$ to $6 \times 10^{18} \text{ cm}^{-3}$. The maximum gain values, dependent on carrier concentration, are illustrated in Fig. 11.

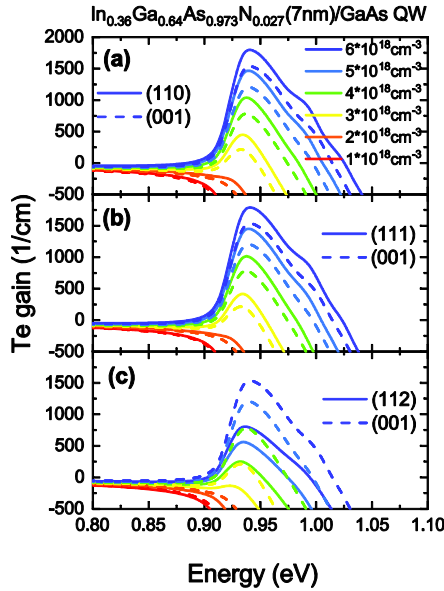


Fig. 10. Material gain calculated for $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}_{0.973}\text{N}_{0.027}/\text{GaAs}$ QW grown on directions: (a) (001) dash line, (110) solid line, (b) (001) dash line, (111) solid line, (c) (001) dash line, (112) solid line. Calculations were performed for carrier concentrations from $1 \times 10^{18} \text{ cm}^{-3}$ to $6 \times 10^{18} \text{ cm}^{-3}$.

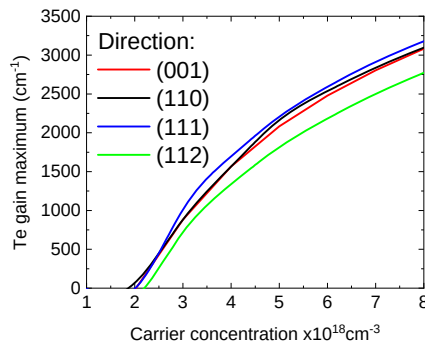


Fig. 11. Gain peak for TE mode vs carrier's concentration for various directions of growth.

Notably, there are discernible differences in the gain values calculated for various crystallographic orientations. Specifically, directions (110) and (111) yield higher values compared to the standard (001) direction, while direction (112) results in smaller values. This correlation is attributed to the band structure calculations. The curves in the valence bands

exhibit an upward trend, which is associated with lower gain values. The changes in carrier distribution within the valence band are depicted in Fig. 12. Carrier distributions were precisely computed using the Eqs. (34) and (35), with density of states determined from Eq. (36), with a fixed carrier concentration of $5 \times 10^{18} \text{ cm}^{-3}$ for each direction, namely, (001), (110), (111), and (112). The color map, transitioning from blue to red, represents carrier localization calculated under each scenario. Fig. 12 also includes the potential shape in the valence band and the hole Fermi level calculated for the given carrier concentration.

8. Conclusions

In this paper we described method of determining band structure and material gain for $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}_{0.973}\text{N}_{0.027}/\text{GaAs}$ material system on arbitrary oriented substrates. We used the 8-band kp method. We presented general expressions for arbitrary orientations of the substrate. Detailed results of band structure are shown for quantum wells grown on (001)-, (110)-, (111)- and (112)-oriented substrates. Band structure depends on the direction of growth as well as resulting strain changes.

Our results indicate that for $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}_{0.973}\text{N}_{0.027}/\text{GaAs}$ quantum wells and carrier concentrations $1 - 6 \times 10^{18} \text{ cm}^{-3}$ (typical for semiconductor lasers) gain spectra are affected by orientation of the substrate. One observes an increase of gain peak (compared to (001) orientation) for (110) and (111) directions.

As shown by our simulation results, the growth direction significantly affects band structure and also material gain. Therefore, it can be considered as an additional parameter used in the design and optimization of optoelectronic devices.

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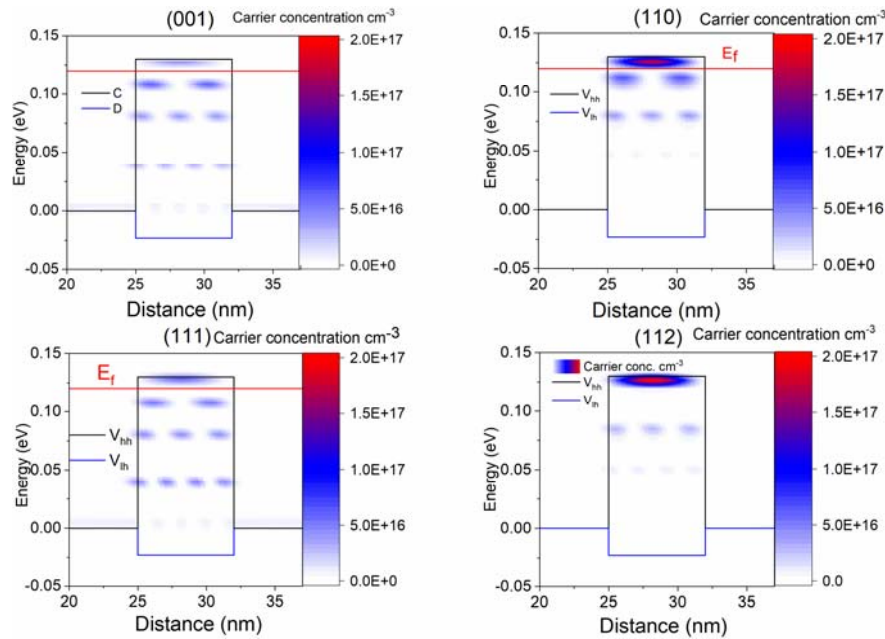


Fig. 12. Carrier distribution (P) as a function of distance and energy for substrates oriented along (001), (110), (111), and (112). These calculations were performed for a fixed carrier concentration of $5 \times 10^{18} \text{ cm}^{-3}$. The red line represents the Fermi level's position within the valence band.

A Study on the Parameters Affecting Clock Comparisons Using Global Navigation Satellite Systems

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Abstract: navigation satellites are reliable and cost-effective means that can serve as an intermediate and efficient facility for comparing remote clocks, eliminating the technical challenges associated with physically moving clocks. Historically, the Global Positioning System (GPS) was the only Global Navigation Satellite System (GNSS) that is used in clock comparisons through observing the same satellites at the same time. However, the evolution of other fully operational GNSS, has opened up alternative avenues for distant clock comparisons through the Common-View (CV) technique. Typically, there are many parameters affecting the stability and accuracy of CV clock comparisons. Some of them are related to the type of GNSS, while others are related to the laboratories and clocks being compared. So, identifying the effect of each parameter on the comparison results is always a hot topic for research. This paper builds upon a previous research work done by the author. The main focus of this paper revolves around a thorough analysis of different factors affecting CV clock comparisons using different GNSSs, including the effect of the number of the satellite vehicles utilized, the effect of the geographical distance between laboratories, and their impact on the number of common observations. Additionally, the study delves into the stability and accuracy of comparison results and the correlation between them.

To conduct this study, the timing data from ten pairs of national time and frequency laboratories were analyzed during a period of 30 days. The ten laboratories are from a total of eight countries, including the United States of America, Germany, the United Kingdom, China, the Netherlands, Kazakhstan, the Czech Republic, and Hong Kong.

Keywords: Clock comparisons, GNSS, Common-view technique, Time transfer stability, Time transfer accuracy.

1. Introduction

Atomic clocks are known for their high precision and stability; however, they can be negatively affected by vibrations and environmental changes. During international comparisons between atomic clocks, transporting one clock to the location of another may render the results invalid upon its return. Therefore, the comparison procedures should be executed without moving the clocks. Using an intermediate facility for comparing distant atomic clocks is the

recommended solution. The intermediate facility can be a Geo-stationary Earth Orbit (GEO) satellite, navigation satellite, communication satellite, or optical fiber link.

There are two famous methods for comparing precise clocks via navigational satellites: the one-way method and the common-view method. There is also a third method that uses communication satellites, which is the Two-Way Satellite Time and Frequency Transfer (TWSTFT) method [1-5]. In 2020, The National Time Service Center (NTSC) at the Chinese

Academy of Sciences in Xi'an, China, devised a novel method for common-view time transfer utilizing Geostationary Earth Orbit (GEO) satellites [6].

In the one-way time transfer method, the navigational satellite emits signals carrying timing data that are received by a timing receiver hosted by the laboratory. The timing receiver receives, processes, and analyzes the signals, then extracts the time difference between the local clock, connected to the receiver, and the time scale built by the GNSS (GNSST). The calculated time difference is sent on a daily basis to the Bureau International des Poids et Mesures (BIPM) for calculating the UTC [7].

In CV clock comparisons, if the two remote clocks are in common view of at least a single satellite, then the GNSS receivers synchronized to these clocks can receive the same GNSS signals from the common satellite, process the received signals, and calculate the time difference between the local clock and the GNSS time. The common-view technique involves applying the algorithm of the one-way time transfer technique simultaneously at both sites, utilizing the same visible satellites at the same time. Actually, the CV method compares two distant standard clocks to the GNSST, and the resulting data are exchanged to calculate the time difference between the two remote clocks. The primary benefit of CV clock comparisons lies in the cancellation or minimization of common errors contributed by many sources [8, 9]. It is worth mentioning that the Common-view technique using GPS was employed by the BIPM for the calculation of UTC until 2006. [7].

The TWSTFT technique uses communication satellites, and the two remote clocks should host transponders that transmit and receive signals from the communication satellite. The TWSTFT technique is employed in situations where stability of less than a nanosecond is necessary, making it suitable for comparing distant Cesium fountains – currently recognized as the international primary frequency standards. Although sub-nanosecond accuracy can be achieved using the TWSTFT technique, the implementation cost is very high [10].

It is well known that the rotational speed of GEO satellites around the Earth is equal to the rotational speed of the Earth. Hence, they appear stationary relative to any fixed point on the earth. This feature of GEO satellites makes them suitable for CV clock comparisons because they have continuous coverage over a specific area on the Earth. The precision of CV clock comparisons via GEO satellites was superior to GPS CV technique. Moreover, it was found that the root mean square (RMS) of the time difference is about 1 ns compared to TWSTFT [6, 11, 12].

The CV technique is accurate, reliable, and cheap technique for comparing distant standard clocks. Previously, GPS was the sole GNSS through which CV comparisons could be made. There are technical directives specially designed to standardize GPS time receiver software. The objective was to enhance the accuracy of GPS common-view time transfer. Now,

there are many other fully operational GNSSs that can be used in standard clocks' comparisons [13-17].

In a previous study, the author demonstrated variations in the stability of one-way time transfer among different GNSS. Additionally, it was observed that satellites within the same GNSS may exhibit distinct behaviors [18]. In a recent research work done by the author, the performance of the four currently available GNSSs was studied when they are used in the common-view technique [19].

In this paper, the author validated the results obtained in the one-way clock comparisons mentioned in [18], with a focus on the CV technique. Moreover, the investigations mentioned at [19] were extended to explore the impact of the distance between laboratories on various aspects, including the number of common observations in clocks' comparison, the daily time transfer stability, and the time difference between the two clocks in the CV clock comparisons using different GNSSs.

2. The Stability of CV Clock Comparisons Using a Different Number of the Common Observed Satellite Vehicles

In a previous study done by the author [18], it was demonstrated that noticeable time transfer stability distinctions exist both among various GNSSs and among the individual satellites within the same GNSS in the one-way time transfer, Fig. 1. Galileo exhibited superior stability, while GPS showcased the highest visibility. Consequently, the conclusion was drawn that the variations in behavior among satellites within the same GNSS underline the importance of implementing selection criteria when choosing satellites for any time or frequency comparison [18].

Since the CV technique imply applying the one-way technique at both laboratories, then, in this paper, the author applied a similar analysis and calculated the instability of the CV time transfer during an observation period of 30 days (the same period used in [18]) using all the visible satellites, using the least instable satellite, using the most instable satellite, and using a group of four satellites.

Fig. 2 shows the instability of results when making a clock comparison between the British Metrology Institute (National Physical Laboratory (NPL)) and the German Metrology institute (Physikalisch-Technische Bundesanstalt (PTB)) during an observation period of 30 days, from MJD 59853 to MJD 59882. Both laboratories are operating multi-system and multi-channel dual-frequency GNSS receivers. The analyzed data of NPL is belonging to their NPL3 receiver while the analyzed data of PTB belongs to their PT13 receiver. It is worth noting that the distance between Teddington, the location of NPL, and Braunschweig, the location of PTB, is 751 Km approximately.

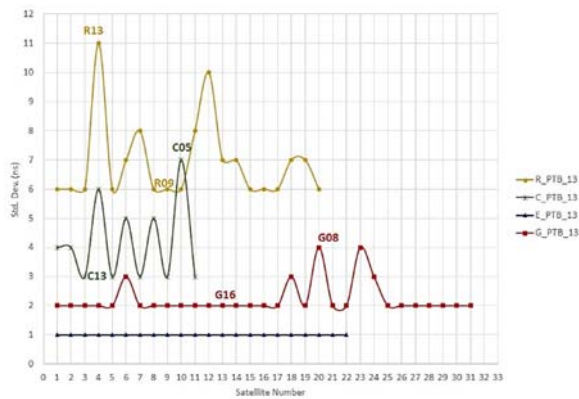


Fig. 1. The instability of the satellites in four GNSS for an observation period of 30 days. R: GLONASS; C: BeiDou-2; E: Galileo; G: GPS; PTB13: the analysed data belong to the Golden Receiver (PT13) of the German metrology institute (PTB). NRC_C4: the analyzed data belong to C4 receiver hosted by the national metrology institute of Canada (NRC) [18].

For GPS, Galileo, and GLONASS, it is clear that the least time transfer instability was obtained when we considered all the commonly visible satellites. For BeiDou-2, the time transfer instability is almost the same when using all or subset of the visible satellites, that is because the low number of the visible satellites.

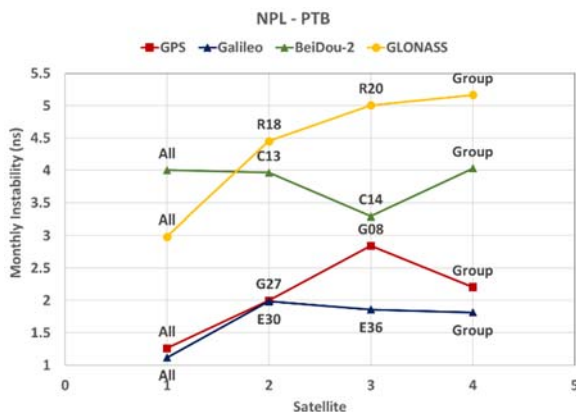


Fig. 2. The instability of the common-view clock comparison between NPL and PTB for a time period of 30 days using GPS, Galileo, GLONASS, and BeiDou-2 using all the commonly visible satellites, single satellite, and a group of four satellites.

3. The Effect of the Distance Between Laboratories on the Number of Commonly Recorded Data Points in CV Clock Comparisons

In a previous research paper [19], the author studied the instability of time transfer between NPL and PTB when using GPS, Galileo, GLONASS, and BeiDou-2. It was proven that the CV time difference

instability between NPL and PTB varies among the different GNSSs, with BeiDou-2 exhibiting the least stable time transfer.

In this paper the author extends the study made at [19] and studies the effect of distance between the two laboratories on the instability of the comparison results using different GNSSs. Nine pairs of laboratories were selected to conduct this study. These pairs are as follows:

- 1) U.S. Naval Observatory (USNO), Washington DC, United States of America and the U.S. Naval Research Laboratory (NRL), Washington DC, United States of America;
- 2) U.S. Naval Observatory (USNO), Washington DC, United States of America and the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany;
- 3) U.S. Naval Observatory (USNO), Washington DC, United States of America and the National Time Service Center of China (NTSC), Lintong, China;
- 4) Dutch Metrology Institute (VSL), Delft, the Netherlands and the European Space Agency (ESA), Noordwijk, the Netherlands;
- 5) Dutch Metrology Institute (VSL), Delft, the Netherlands and Kazakhstan Institute of Standardization and Metrology (KZ), Astana, Kazakhstan;
- 6) Dutch Metrology Institute (VSL), Delft, the Netherlands and the Standards and Calibration Laboratory, Hong Kong;
- 7) National Time Service Center of China (NTSC), Lintong, China and Joint Atomic Time Commission (JATC), Lintong, China;
- 8) National Time Service Center of China (NTSC), Lintong, China and the National Institute of Metrology (Thailand), Pathumthani, Thailand;
- 9) National Time Service Center of China (NTSC), Lintong, China and the Institute of Photonics and Electronics, Czech Academy of Sciences (IPE/ASCR) (TP), Praha, Czech Republic.

The clocks of the first three pairs (USNO-NRL, USNO-PTB, USNO-NTSC) were compared using GPS. The clocks of the second three pairs (VSL-ESA, VSL-KZ, VSL-SCL) were compared using Galileo, and the clocks of the third three pairs (NTSC-JATC, NTSC-NIMT, NTSC-TP) were compared using BeiDou-3. Table 1 displays the model and code of the timing receiver hosted by each laboratory. Table 2 presents the distance between each pair of laboratories and the number of common data points recorded by the receivers while observing the same satellites during a testing period of 30 days (MJD 60173 to MJD 60203).

Regarding GPS, the table 2 illustrates that with an increase of 119 % in the distance between the two laboratories, the number of common data points dropped by 50 %. Additionally, an increase of 250 % in the distance resulted in 95 % drop in the common data points.

Table 1. The type and code of the timing receiver of each laboratory.

Laboratory	Receiver Model	Receiver Code
USNO	NovAtel ProPak-V3	US06
NRL	PolaRx5TR	RL5B
PTB	PolaRx5TR	PT13
NTSC	GTR55	NT03
VSL	PolaRx4TR PRO	VS06
ESA	POLARX5TR	ES07
KZ	GTR55	KZ04
SCL	PolaRx5TR	SC05
JATC	GTR55	JA02
NIMT	GTR55	MTTI
TP	GTR55	TP02

For Galileo, an increase of 152 % in the distance between the two laboratories led to a reduction of 61 % in the common data points, and an increase of 265 % resulted in 75 % drop.

In the case of BeiDou-3, an increase of 50 % in the distance between the two laboratories caused 16 % reduction in the common data points, and an increase of 252 % led to 68 % drop. Fig. 3 shows clearly the relation between the distance between laboratories and the number of the corresponding commonly recorded data points for GPS, Galileo, and BeiDou-3.

Table 2. The number of common data points and the distance between laboratory pairs.

GNSS	GPS		
(Lab1 - Lab2)	USNO - NRL	USNO - PTB	USNO - NTSC
Number of common Observations	22971	11589	1174
Distance (Km)	55	6547	13772
GNSS	Galileo		
(Lab1 - Lab2)	VSL - ESA	VSL - KZ	VSL - SCL
Number of common Observations	14559	5686	3617
Distance (Km)	35	5331	9304
GNSS	BeiDou-3		
(Lab1 - Lab2)	NTSC - JATC	NTSC - NIMT	NTSC - TP
Number of common Observations	39153	33070	12346
Distance (Km)	41.7	2086	10532

4. The Effect of Distance Between Laboratories on the Stability of CV Clock Comparisons

To investigate the impact of the distance between the laboratories engaged in the comparison on the instability of results of the CV clock comparison, we conducted clock comparisons among the laboratory pairs illustrated in Table 2.

Fig. 4 illustrates the instability of the CV clock comparison when we compared three pairs of clocks that are separated by 55 km, 6547 km, and 13772 km using GPS. It is clear that the most stable results are obtained from the closest laboratories and as the distance between the two laboratories increases, the stability of the results worsens.

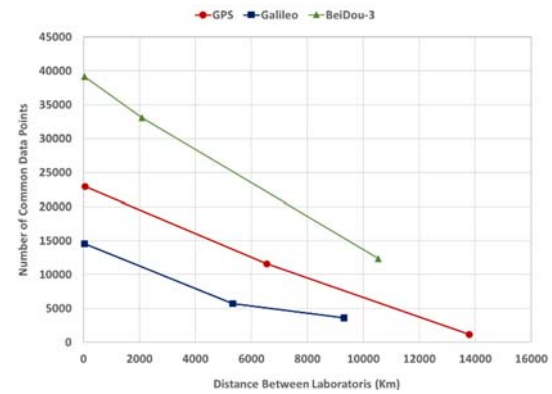
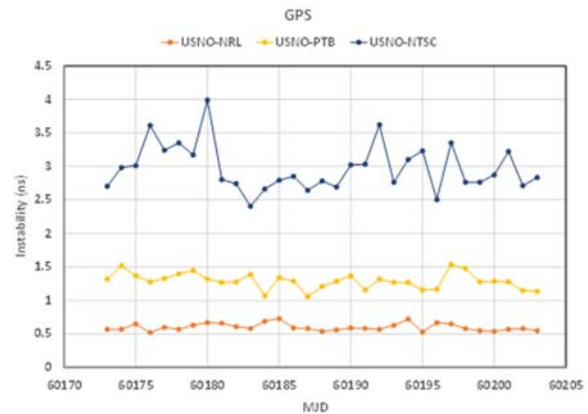
**Fig. 3.** The number of the common data points versus the distance between laboratories.**Fig. 4.** The instability of the common-view clock comparison among three pairs of laboratories separated by 55 km, 6547 km, and 13772 km using all visible GPS satellites.

Fig. 5 demonstrates the instability in CV clock comparison as we compared three pairs of clocks separated by 35 km, 5331 km, and 9304 km with the use of the European GNSS, Galileo. The distance, in this case, appears to have a negligible impact on the stability of clock comparisons, especially when the distance between the two laboratories is in the range of few thousand kilometers.

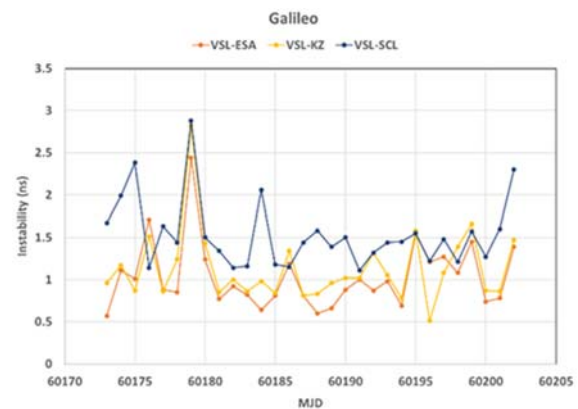
**Fig. 5.** The instability of the common-view clock comparison among three pairs of laboratories separated by 35 km, 5331 km, and 9304 km using all visible Galileo satellites.

Fig. 6 depicts the common-view clock comparison instability resulting from comparing clocks in three pairs of laboratories distant by 41.7 km, 2086 km, and 10532 km using the Chinese GNSS, BeiDou-3. It seems that using BeiDou-3 satellites in common-view clock comparisons yields a performance similar to that of using GPS satellites.

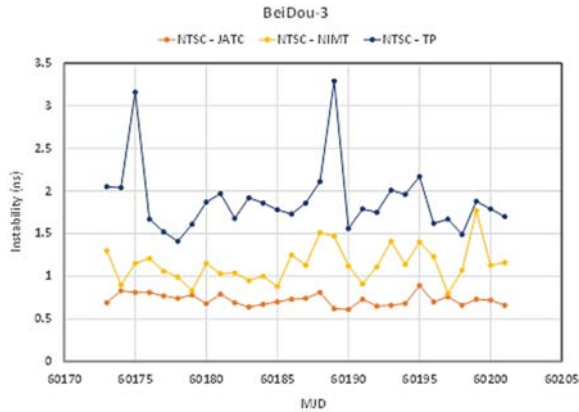


Fig. 6. The instability of the common-view clock comparison among three pairs of laboratories distant by 41.7 km, 2086 km, and 10532 km using all visible BeiDou-3 satellites.

5. The Effect of Distance Between Laboratories on the Accuracy of Clock Comparisons Using the CV Technique

Typically, the accuracy of the time difference doesn't mirror the accuracy of the GNSS satellites in CV clock comparisons, as the dominant factor affecting accuracy is the quality of calibrating the GNSS receivers at both laboratories. On the other hand, when time transfer stability is influenced by the distance between the two clocks being calibrated, it is expected that the distance between the clocks affects their time difference.

To study the effect of the distance between the laboratories on the time difference between their clocks, we need first to determine the true time difference between them. So, we have to obtain the time difference between the national time scale at each laboratory k ($UTC(k)$) and the Coordinated Universal Time (UTC or UTC_r) calculated by the BIPM, $[UTC/UTC_r - UTC(k)]$. Second, we calculate the true time difference between the two laboratories k_1 and k_2 ($UTC(k_1) - UTC(k_2)$). Then, we compare the true time difference to the time difference resulted from using the CV clock comparison.

Note: The daily values of the time differences $[UTC_r - UTC(k)]$ can be obtained from the BIPM ftp server: <https://www.bipm.org/en/time-ftp/utcr>. Given that UTC_r is the rapid version of UTC .

To investigate how the distance between laboratories impacts the time difference between the two clocks, we selected the laboratory pairs

(USNO-NRL), (USNO-PTB), and (USNO-NTSC) that are distant by 55 Km, 6547 Km, and 13772 Km respectively. A CV clock comparison was conducted between each pair using GPS.

Fig. 7 shows the time difference $[UTC(USNO) - UTC(NRL)]$ that is calculated using the BIPM ftp server and the CV time difference between both laboratories using the data extracted from their timing receivers. Fig. 8 shows the same time difference comparison between USNO and PTB, while Fig. 9 shows the comparison results between USNO and NTSC.

In order to grasp how the distance between the laboratories influences the time difference among their clocks, we examined the correlation between Fig. 4 and Figs. 7, 8, and 9. Given that the results of the four figures are calculated during the same observation period (from MJD 60173 to MJD 60203).

The instability of time transfer between USNO and NRL, as shown in Fig. 4, exhibited the least instability that is characterized by low and semi-periodic fluctuations. These features were reflected on the time difference recorded during the common-view clock comparison, as illustrated in Fig. 7, which displayed low and semi-periodic deviations from the true time difference.

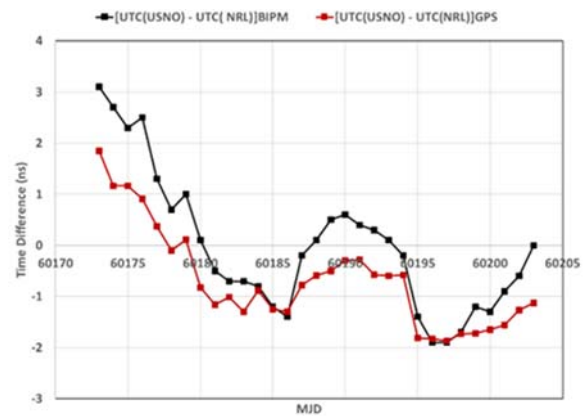


Fig. 7. The true and the CV time difference between USNO and NRL.

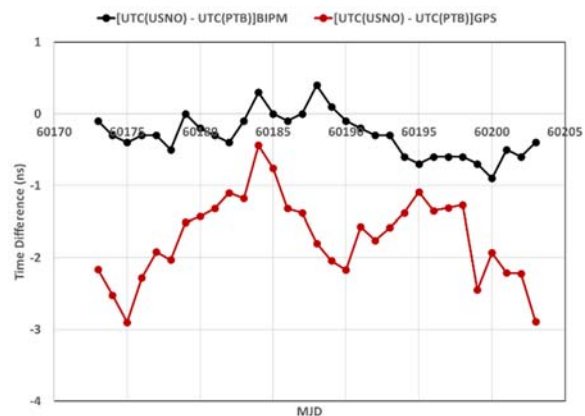


Fig. 8. The true and the CV time difference between USNO and PTB.

Fig. 4 reveals that the time transfer instability between USNO and PTB is higher than the instability between USNO and NRL and displaying semi-periodic fluctuations too. These characteristics are evident in the time difference recorded during the common-view clock comparison in Fig. 8, where there are consistent high and semi-periodic deviations from the true time difference.

Fig. 4 reveals the highest instability in time transfer between USNO and NTSC that is characterized by very high fluctuations. This instability is mirrored in the time difference during common-view clock comparison shown in Fig. 9.

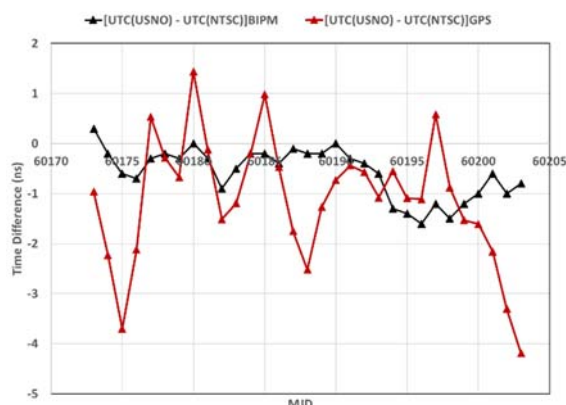


Fig. 9. The true and the CV time difference between USNO and NTSC.

6. Conclusion

Navigation satellites stand out as a reliable and cost-effective facility to be used in clock comparisons. In the past, the CV clock comparisons were primarily utilizing GPS for comparing distant clocks. However, with the advent of multiple fully operational GNSSs, including GLONASS, Galileo, and BeiDou, these systems have become viable alternatives for conducting distant clock comparisons through the common-view technique.

This paper validates previous one-way clock comparison results presented in [18], with a specific focus on the common-view technique. Moreover, extending the investigations outlined in paper [19]. The core emphasis of this research lies in scrutinizing the influence of various factors on the results of the CV clock comparisons, such as the number of satellite vehicles used and the distance between laboratories and their impact on the number of common observations as well as the stability and accuracy of the comparison results.

For GPS, Galileo, and GLONASS, the most stable results were achieved when considering signals from all observable satellites. Conversely, for BeiDou-2, the stability of results remains nearly unchanged, whether considering all visible satellites or only a subset, this is attributed to the limited number of satellites in BeiDou-2. For all GNSSs, the findings of this research

indicate that the number of commonly observed data points is directly affected by the geographical separation between laboratories. BeiDou-3 demonstrated the highest count of common data points for small, medium, and large distances (up to 10,000 km), followed by GPS and then Galileo.

In the case of Galileo, the effect of the distance between laboratories is almost negligible on the stability of the comparison results. However, it negatively affects the stability in the case of GPS and BeiDou-3, given their similar performance.

For GPS, the relationship between the distance between laboratories and the accuracy of the results is evidently correlated with the stability of time transfer. A considerable correlation is observed between the stability curve and the accuracy curve.

In summary, enhancing the stability of the one-way clock comparisons can be achieved by exclusively selecting the most stable satellites. However, when it comes to CV comparisons, it is advisable to include all commonly visible satellites in the clock comparison process. The stability of the CV clock comparisons using BeiDou-3 is comparable to GPS but BeiDou-3 exhibits a higher number of common data points than GPS over the same observation period. The geographical distance between laboratories does not impact considerably the stability of CV clock comparisons when Galileo is utilized.

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Double Input Convolutional Neural Network Model for Determining Heights of Figures in 2D Images from their Shadows

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Abstract: This research developed a model using convolutional neural network (CNN) architecture for pattern detection and feature extraction from shadows and shapes in images. The dataset was constructed with photographic images of figures, with their respective shadows cast from different angles and locations. A DataFrame was constructed that combined with images of the figures improves the accuracy of the algorithm. Therefore, the presented model offers a favorable structure for estimating the height of 2D figures from shadows in images. The convolutional design makes it suitable for learning complex patterns in visual data, while the linear activation function in the output layer enables regression tasks. Thus, the optimized CNN model represents an automated process that learns to map patterns in shadow images to corresponding heights

Keywords: Shadows, Shapes, Convolutional neural network, Dataset, DataFrame, 2D, Height.

1. Introduction

When estimating the height of a figure or object contained in a 2D image from its shadow is a complex process and is encountered under different lighting conditions. This has become a major challenge, as the need for an accurate model that can estimate the geometry of the object and the way the light hits it. However, estimating the height of a figure or object in a 2D image from its shadow becomes a more complex problem due to the lack of information. In this context, the use of neural networks has become a valuable tool to address this research problem, and a solution based on convolutional neural networks for height prediction

from its shadow is presented. The proposed model uses a convolutional neural network architecture with regression to extract relevant image and shadow features to perform figure or shape height prediction.

In [31] (Khan, M.S.U. et al. 2022) Three-dimensional (3D) reconstruction from a two-dimensional (2D) image is a prominent challenge in the field of image processing and computer vision. Traditionally considered an ill-conditioned problem in terms of optimization, recent advances in machine learning techniques have significantly boosted the efficiency of 3D reconstruction. The complexity rises when dealing with objects with complex deformations or lacking texture, due to the possibility of projecting

multiple 3D objects from the same 2D plane. This research provides a comprehensive review of studies conducted between 2018 and 2021 related to 3D reconstruction from a single perspective, especially highlighting deep learning-based methods. A barrier to direct comparison between the reviewed methods lies in the absence of standardized datasets and the diversity of methods for representing 3D shapes.

The review covers different reconstruction techniques, such as depth map generation, surface normal calculation, point cloud creation and mesh shaping. It also examines various loss functions and metrics that are employed for both training and evaluation of deep learning models in the 3D reconstruction task. This analysis provides a detailed overview of current approaches and their methodologies, highlighting the evolution and progress in this field of research. It also formulates several interesting conclusions, such as three-dimensional (3D) reconstruction from a monocular image is recognized as a complex problem in the field of computer vision, largely due to the lack of a standardized approach to represent 3D shapes and the scarcity of datasets covering a sufficient diversity of objects. This paper argues that real-world 3D data are limited and collecting them is inherently challenging, especially in the case of untextured surfaces, where datasets are even scarcer. There are also generative antagonistic networks (GANs), which have proven to be remarkably efficient and fast, reaching point cloud generation frequencies of 250 Hz, which is favorable for real-time applications. In addition, the adoption of transformers in vision tasks is emerging as a promising technique, with a specific network improving low-resolution 3D reconstruction and intersection index over union (IoU) on the ShapeNet dataset. In summary, it is a paper that suggests that there is a promising path towards improved monocular 3D reconstruction, although there remains a need for expansion of datasets and standardization of techniques to effectively compare methods and results between different investigations.

For the training and validation of the proposed model, a dataset was used that includes photographs of a diversity of geometric figures, multiple shapes and shadows under various lighting conditions. With this dataset, the validation training and testing process of the model was performed to have the ability to estimate the height of the figures, which suggests or represents a promising solution for estimating the height of figures in two-dimensional images based on their shadows. Future research will focus on judging the accuracy and efficiency of this innovative method by comparing it to other pre-existing algorithms that also estimate the height of objects from their shadows.

The proposed model was evaluated with a test data set, achieving remarkable accuracy in estimating object heights compared to previous methods. In essence, the integration of cast shadow data in a learning model plus a DataFrame represented a very good strategy when estimating the height of a figure from its shadow in 2D images.

By applying advanced deep learning techniques, it is possible to process and analyze large volumes of data, leading to increased accuracy in estimating the height of shapes from their shadows. Furthermore, the ability to integrate new geometric shapes and shadows within the image set and used in the model provides an additional variety of information for future research, especially when working with irregular shapes.

Similarly, in [9] (S. Mohajerani, P. Saeedi. 2018), the automatic detection of shadows in images using a segmentation method and the application of Deep Learning is addressed. The study focuses on identifying pixel-level shadow regions in RGB images by extracting shadow features and providing a Convolutional Neural Network (CNN) with the ability to detect shadow patterns both locally and globally.

On the other hand, in [25] (Tao, M. W., Srinivasan, P. P., Hadap, et al. 2017), they developed an algorithm based on dense depth estimation which combines blur and correspondence metrics. In addition, it defines an optimization framework that integrates photographic, depth and shading coherence for light depth-of-field estimation in different scenarios.

1.1. The Shadow

Shadows are defined as segments of a scene that are not directly illuminated by a light source. This definition is extended to identify two distinct categories of shadows. The first is the intrinsic shadow, characterized by the fact that the shadow area is located on the object itself that generates the shadow. The second is cast shadow, which refers to the area of shadow visible on surfaces other than the obstructing object, either the background or other surrounding objects. Within the cast shadow, it is common to differentiate two areas: the umbra, which is the darkest part of the shadow where light is completely blocked, and the penumbra, which is the transition zone where light is partially blocked (Fig. 1).



Fig. 1. Figure and corresponding shadow and Rotation of the light source.

In [4] (Vicente and Samaras, 2014)], recognizes that two-dimensional digital images have features such as textures, edges, shapes, colors and shadows. The latter, in particular, provide critical data that can be exploited by shadow detection techniques to infer relationships between object shape, light sources, and shadowed areas.

Similarly, previous research such as those of [8] (Kriegman and Belhumeur. 1998) and [11] (Knill et al. 1997), cited respectively, have given importance of shadows as indicators of information about the shape and topography of surfaces and objects. These help to identify areas of interest, establish the direction of light sources, and discern geometric details. In this context, the work of (Knill, Mamassian and Kersten. 1997) and Shafer and Kanade (1983), [11] (D. C. Knill, et al. 1997) and [17] (S. A. Shafer, T. Kanade. 1983), respectively, have shown that the intrinsic geometric properties of shadows are particularly valuable. This is because they facilitate the understanding of the interaction between shapes, shadows and illumination, contributing to the perception of the structure and height of the surfaces under study.

In numerous previous works, as indicated in [24] (Hintze, Morse. 2019), the information extracted from the shadow using techniques, methods and algorithms for purposes such as: determining the location of the shape or object, area of interest, direction of the light source, among others, is usually oriented towards its subsequent elimination, where this makes its significance not so remarkable.

In [30] (Huang, X. et al. 2007) presents an approach for shape-from-shading (SFS) estimation. They propose an example-based method that increases the robustness and accuracy of SFS. The heart of this method lies in the use of a database containing synthetically generated appearances of known three-dimensional models. Each pixel in these synthetic images is linked to its corresponding real surface normal. By confronting the input image with this database, the algorithm is able to identify the normal for each point in the image. The method has been tested using a small generic database consisting of 50 spheres of different radii. The results have shown a significant improvement in the quality of reconstruction of both synoptic and real images. The method is particularly effective in reconstructing shapes with minute details, validating its potential for applications in environments where traditional FSS methods fail. The presented study introduces an advanced Shape-from-Shading (SFS) algorithm that improves the estimation of surface gradient maps for intensity-based images. The technique employs sample images with known surface normal as an additional source of information, incorporating them as a constraint term in an energy-minimizing process.

On the other hand, in [12] (Salvador, Cavallaro and Ebrahimi. 2004) it is stated that the shadows in a 2D image contain relevant information about the scene, obtaining the location of the shape or object, the characteristics of the surface and the light source. Techniques are mentioned that are based on models that represent the knowledge of the scene geometry, objects or shapes, the light source, as well as techniques based on properties that identify shadows using characteristics such as geometry, brightness and color of the shadows (Fig. 2).

Similarly, in [12] (Salvador, Cavallaro and Ebrahimi. 2004), general aspects related to digital

image processing are addressed, using convolutional neural networks (CNN) with different data sets (datasets), where the latter are mainly characterized by containing images of geometric primitives and the shadows, they cast according to an illumination source located in a specific location. Similarly, in [2] (Panagopoulos, Hadap, Samaras and Dimitris. 2013) in their research they use synthetic images divided into small rectangular regions, and thus, for each of these it is possible to capture what corresponds to the distribution of intensities and the ability to handle surfaces. At this point, the geometry sections are combined, integrating the intensity distribution into a dictionary that, with all the sections, can generate a hypothesis about that shape.

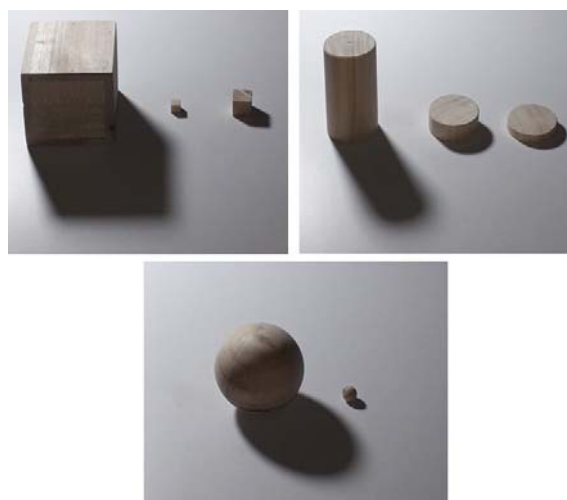


Fig. 2. Types of dataset figures.

Employing the learning model that processes the images of the training set, which with all sections or small regions form a large dictionary, and where the decomposition of an image into shadow and reflectance images describe the brightness perception for these images.

In [1, 13] (Hosseinzadeh, S., Shakeri, M. and Zhang, H. 2005) it is shown that the concept of sections corresponds to a collage of sections with a different reflectance and which are illuminated with an illumination source that varies slowly in intensity, and with shapes that are of a constant scale factor. This learning model with the data set to be generated would be used to determine the surface height and 3D generation of the object or shape, initially taking the information of the shadow it casts on a 2D image. In [12] (Salvador, Cavallaro, Ebrahimi, Touradj. 2004), [7] (G. Liasis, S. Stavrou. 2016) illumination, shadows and reflectance are an integral part of the different scenes, providing relevant information about the shape and appearance of the object.

An innovative deep learning architecture designed to transform a color image into a 3D shape composed of a triangular mesh is presented in [33]. Previous approaches in this field were often limited to 3D shape

representations such as volumes or point clouds, which do not translate easily into usable mesh models. The architecture proposed by the authors departs from these limitations by implementing a graph-based convolutional neural network that generates 3D meshes. This method innovates by progressively deforming an ellipsoid using detailed perceptual features obtained from the input image. To ensure the stability of the deformation process, the researchers adopt a strategy that goes from general to specific (coarse to fine). In addition, various loss functions linked to the mesh structure are introduced, which aim to ensure that the resulting 3D geometry is not only visually appealing, but also physically accurate. Extensive experiments demonstrate that the proposed method is capable of producing mesh models with a superior level of detail and accuracy in 3D shape estimation that outperforms pre-existing state-of-the-art techniques.

In [2] (Panagopoulos, Hadap, and Samaras. 2013) propose the use of a dictionary use of a dictionary (Dictionary) that is confirmed by different patches (Patches) of geometry associated to the image, to a distribution of pixel intensities that can generate that geometry and with the use of larger image regions that allow capturing appearance data, it is possible with a data set and supported in neural networks it is possible to design a model that fits the proposed research.

In [22] (Varol, Shaji, Salzmann, Fua. 2011) has an approach based on deformable shape recovery that can work under complex illumination and on partially textured surfaces. They used an algorithm that performs a learned mapping of the intensity distribution and shape of local surface patches, which is focused on 3D surface shape estimation.

In [14] (D. S. Kim, M. Arsalan, K. R. Park. 2018) they employ a Convolutional Neural Network (CNN) for shadow detection using cameras and using the open database CAVIAR (Context-Aware Vision Using Image-Based Active Recognition). They indicate that in their research it is not computationally expensive both in training and validation and can be adapted to tasks such as image segmentation and has a level of accuracy of other methods.

In [34] (Anny Yuniarti, Nanik Suciati 2019) is a review of 3D reconstruction. Although deep learning techniques have revolutionized image segmentation and object recognition, their application in 3D reconstruction is at a nascent stage. Nevertheless, their potential is considerable and their exploration promises to significantly improve the performance of reconstruction methods. [34] focuses on the literature review specializing in 3D reconstruction from single or multiple images, explicitly excluding RGB-D input. This article is distinguished as one of the first systematic reviews focused on 3D reconstruction through deep learning, providing a comprehensive overview of the most recent and advanced work in this field. The conclusion emphasizes that, although remarkable progress has already been made with the use of deep learning techniques in 3D reconstruction, there is room for improvement.

The content presents an overview of the evaluation metrics used to measure the effectiveness of different representations and methods in 3D reconstruction, focusing on three main types: point clouds, voxels and meshes. Voxel representation faces limitations in resolution and memory consumption, problems that can be mitigated by using octrees or learning to encode and decode 3D point representations, although the latter lacks surface connectivity. On the other hand, meshes have surface connectivity, but involve a combinatorial optimization challenge due to the sampling of vertices from the object surface. Comparing different approaches, it is concluded that ResMeshNet outperforms both the point cloud-based approach (e.g., PSG) and other mesh-based methods (e.g., AtlasNet).

1.2. The Dataset

The experimentation process is carried out under controlled conditions in terms of illumination, shapes and surface. Such conditions were used in the model allowing initially to test the model of the network and that it learned certain characteristics, which is why it was decided to use the different photographs of three geometric shapes on a uniform surface, with a dimmable LED lamp and the shadows corresponding to each shape (Fig. 3). It is important to mention that the data set was oriented with the objective of capturing photographs under different lighting conditions to give an initial knowledge to the neural network.



Fig. 3. Characteristics of the Dataset.

The data set includes 800×600 color photographs (RGB) of various geometric shapes of various colors, taken from a distance of 90 cm from the edge of the surface. The surface where the shape or object is located is white, smooth, does not reflect light, and is made of white matte adhesive vinyl. The surface has a size of 90 cm and a diameter of 180 cm, was designed circular to facilitate the displacement of the LED lamp, and is made of MDF (Medium Density Board) wood of 9 mm (Fig. 4).

The model integrates 16 layers, has a total number of parameters: 153985, all parameters are trainable. The architecture is designed to extract and learn features from both the images of the figures and their respective shadows, then combining this information to make a prediction of the height of the figures (see

Fig. 5). In [28] (René, J. et al. 2023) this model has a dual-input CNN is structured to perform regression tasks on images. It was designed with the extraction of significant features from two different input sources in mind, processing them in parallel and then combining this extracted information to generate a unified and better-informed prediction. With nearly 154000 trainable parameters, this architecture offers deep learning capability while maintaining a manageable, efficient size for training and deployment. Its modular and structured design facilitates fine-tuning, as well as additional optimizations to further improve performance and accuracy for specific image regression tasks.



Fig. 4. Mock-up for taking photographs.

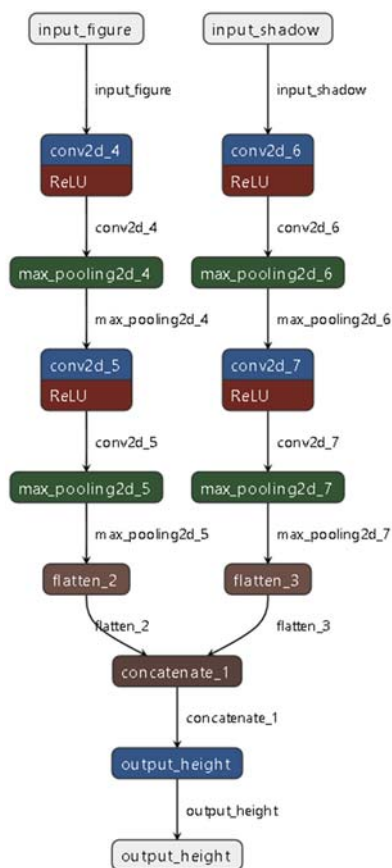


Fig. 5. Dual-Input Convolutional Neural Network Architecture.

1.3. Model Description

With the research conducted, it is proposed to use and/or design a convolutional neural network, which through the training of a set of data will provide the necessary knowledge to predict the height of an object or shape with the projected shadow. With the learning process, it is expected that the network, by using as input information the shadow cast by the shape or object in a 2D image, will predict or determine the height of the object in question. The data set (Dataset) was designed and developed with objects and/or basic geometric shapes (sphere, cube, cylinder) to perform the experimentation in a controlled manner, since after this proposal and as a future work it is expected to increase the data set with more complex shapes and shadows. The total amount of images in the dataset is approximately 4500 color photographs and for each shape, there are 1500 photographs (see Table 1), [28] (René, J. et al. 2023).

Table 1. Height Distribution of Geometric Shapes.

Figure	Color	Measurement (cm)	Quantity
Cube	Brown	1	1
Cube	Brown	1,5	1
Cube	Brown	2	1
Cube	Brown	3	1
Cube	Brown	4	1
Cube	Brown	5	1
Cube	Rubik's Cube	5,5	1
Cube	Brown	6	1
Cube	Rubik's Cube	6,5	1
Cube	Brown	7	1
Cube	Brown	8	1
Cube	Brown	9	1
Cube	Brown	10	1
Total Cubes			13
Cylinder	Brown	1	1
Cylinder	Brown	2	1
Cylinder	Brown	3	1
Cylinder	Brown	4	1
Cylinder	Brown	5	1
Cylinder	Brown	6	1
Cylinder	Brown	7	1
Cylinder	Brown	8	1
Cylinder	Brown	9	1
Cylinder	Brown	10	1
Cylinder	Brown	10,5	1
Total Cylinder			11
Sphere	Brown	1	1
Sphere	White	1,5	1
Sphere	White	2	3
Sphere	Brown	2,5	1
Sphere	White, Yellow, Blue	3	3
Sphere	Brown, Blue with yellow	3,5	2
Sphere	Yellow, White, Orange, Pink	4	4
Sphere	Brown, Yellow	4,5	2
Sphere	Brown	5	1
Sphere	Brown, Yellow, Green, White	6	3
Sphere	Brown, White	7	2
Sphere	Blue, Violet	8	2
Sphere	White, Red	8,5	2
Sphere	Yellow	9	1
Total Sphere			28

It is important to note that the proposed model (Figs. 6 and 7) uses geometry of three-dimensional shapes of the objects or shapes with the corresponding shadow from different locations in the plane and generated by a single light source. The latter is rotated around the figure to obtain shadows from different

angles. The light source is located 90 centimeters from the center of the object to the base of the lamp and the heights of the lamp vary from 45 centimeters (cm) to 50 centimeters (cm) so that the different shadows are observable on the surface under varying intensities of illumination (see Fig. 1), [28] (René, J. et al. 2023).

Layer (type)	Output Shape	Param #	Connected to
input_figure (InputLayer)	[(None, 128, 128, 3) 0		
input_shadow (InputLayer)	[(None, 128, 128, 3) 0		
conv2d (Conv2D)	(None, 126, 126, 32) 896		input_figure[0][0]
conv2d_2 (Conv2D)	(None, 126, 126, 32) 896		input_shadow[0][0]
max_pooling2d (MaxPooling2D)	(None, 63, 63, 32) 0		conv2d[0][0]
max_pooling2d_2 (MaxPooling2D)	(None, 63, 63, 32) 0		conv2d_2[0][0]
conv2d_1 (Conv2D)	(None, 61, 61, 64) 18496		max_pooling2d[0][0]
conv2d_3 (Conv2D)	(None, 61, 61, 64) 18496		max_pooling2d_2[0][0]
max_pooling2d_1 (MaxPooling2D)	(None, 30, 30, 64) 0		conv2d_1[0][0]
max_pooling2d_3 (MaxPooling2D)	(None, 30, 30, 64) 0		conv2d_3[0][0]
flatten (Flatten)	(None, 57600) 0		max_pooling2d_1[0][0]
flatten_1 (Flatten)	(None, 57600) 0		max_pooling2d_3[0][0]
concatenate (Concatenate)	(None, 115200) 0		flatten[0][0] flatten_1[0][0]
output_height (Dense)	(None, 1)	115201	concatenate[0][0]

Total params: 153,985
Trainable params: 153,985
Non-trainable params: 0

Fig. 6. Model Architecture.

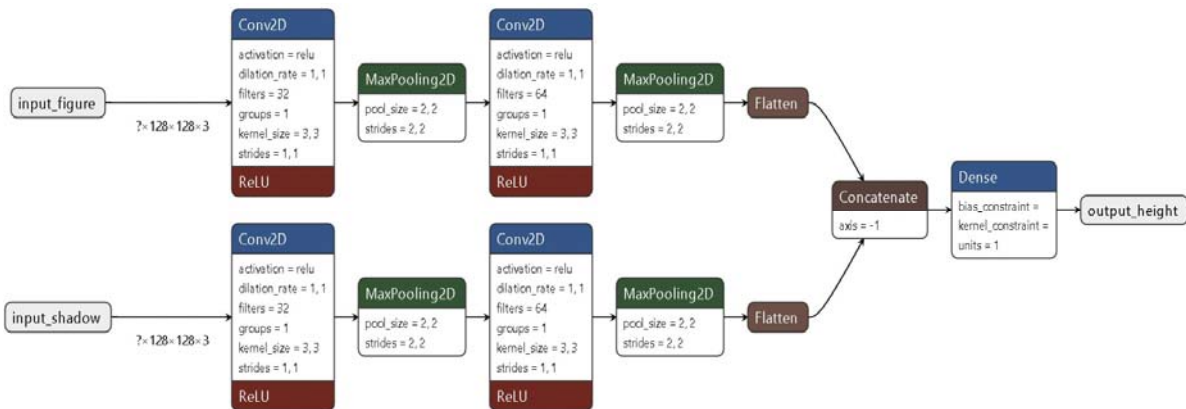


Fig. 7. General Scheme of the Proposed Model (horizontal view). (Reported using Netron. <https://netron.app/>).

General Scheme of the Proposed Model (horizontal view). Is a regression convolutional neural network architecture designed to process two distinct inputs: from an image and from its corresponding shadow. Each input was initially processed by two parallel convolutional layers (conv2d and conv2d_2), both conformed with filters of size 3×3 and a depth of

32, using the ReLU activation function to introduce nonlinearities.

After this first stage, the features extracted from both inputs were MaxPooling (max_pooling2d and max_pooling2d_2) with a pool size of 2×2 and strides of 2, which reduces the dimensionality obtaining the most relevant features. Next, the resulting feature

maps went through a second set of convolutional layers (conv2d_1 and conv2d_3) which extended the filter depth to 64, keeping the same kernel size and ReLU activation function. A second MaxPooling operation (max_pooling2d_1 and max_pooling2d_3) followed this layer, further consolidating the relevant features.

The data were then flattened with the flatten and flatten_1 layers in order to transform the multidimensional output into a one-dimensional vector, which is necessary for the concatenation of the data coming from the two branches of the network model. This concatenation was performed along a common axis (axis = -1), which is the last axis (dimension) in a tensor, allowing the fusion (concatenation) of the image data and their shadows into a joint representation. Finally, the network produced a single output (output_height) through a dense layer, which was configured with a single node and used a kernel of size (115200×1), suggesting that the flattened data were of significant dimension before the final operation. This output layer provided a scalar estimate, possibly related to the height of the object depicted in the image, which is a common interpretation in regression tasks with neural networks in the context of image processing.

With this knowledge, it is expected that the convolutional neural network will be able to predict the height of the shapes from their shadow. This height measurement is given in centimeters (units) using as input image only the projected shadow. Thus, it is initially expected to effectively estimate the height of the shape or object corresponding to the shadow, which is one of the challenges of the research. Moreover, there is additional information in the dataset that combined with appropriate 2D to 3D shape reconstruction algorithms it is possible to obtain the reconstruction of the shape according to the height established from the shadow.

In [21] (M. Daum, G. Dudek. 1998) the reconstruction of 3D surfaces from shadows is reported. Here, the movement of shadows that are cast is used to obtain information about the scene structure, based on the collection of images from a fixed point as an illumination source moves. As a result, a 3D scene reconstruction algorithm is obtained taking into account the trajectories of the light source.

On the other hand, in [26] (Huang, X., Gao, J., et al. 2007) their research addresses shape estimation from shading (SFS) which aim to solve a problem with few constraints to estimate the depth map from a single image, developing an example-based method to improve the accuracy of (SFS), improving the reconstruction quality from real images of different shapes by obtaining prior knowledge of their appearance for three-dimensional shape recognition.

Similarly in the proposal in [20] (E. Prados, O. Faugeras. 2006) with the shape from shading (SFS) and with a single image they estimate the 3D shape of a surface, where in diffuse surface the position of the illumination source is not known and where the reflectance map is not known.

In [15] (S. Savarese, et al. 2007), [16] (S. Savarese, et al. 2002) and [5] (R. Gouiaa, J. Meunier. 2014) they propose a new method to recover a shape from shadow (SFS). These projected shadows are relevant information about the shape of objects, discovering cavities that are not available from clues such as occluded boundaries. This method is called "occluding boundaries". According to the volume occupied by an object, it is possible to identify and sculpt the regions of the volume that present inconsistencies with the pattern observed in the shadows. In summary, their proposal is a reconstruction system to recover the shape from silhouettes and shadow carving where shadow carving is used to carve the concavities and silhouettes are used to reconstruct the initial conservative estimate of the shape of the object.

On the other hand, in [3] (D. Forsyth, A. Zisserman. 1991), he shows how mutual illumination and image irradiance within an image give rise to more complex structures.

Similarly, in [27] (Atkinson, G. A., & Hancock, E. R. 2007), research presents a novel method for the reconstruction of 3D surfaces with polarization and shading information from two views. They use Fresnel theory in image processing to obtain estimates of the surface normal. Here they emphasize how the measured pixel brightness's depend on the surface orientation combined with the refined estimates to determine the correspondence between two views of an object. In [19] (R. Liu, S. Menon, et al. 2022) they address 3D reconstruction when the object structure is partially or totally occluded. They introduce into the method projected shadows of an unobserved object, to perform the inference of the possible 3D volume to which it corresponds. The "inheritable" imaging model allows to jointly infer both the 3D shape of the object, its location and that of the illumination source.

In [19] (R. Liu, S. Menon, et al. 2022) they address 3D reconstruction when the object structure is partially or totally occluded. They introduce into the method projected shadows of an unobserved object, to perform the inference of the possible 3D volume to which it corresponds. The "inheritable" imaging model allows to jointly infer both the 3D shape of the object, its location and that of the illumination source. The advantage of this approach is the estimation of multiple 3D scenes from shadows.

The data set is organized in folders and within each subfolder, there are images corresponding to each geometric shape, the shadow, the height. It is important to point out that with the experimentation process, the length of the shadow and the angle of the light source were added to the Dataset already created, improving the accuracy of the model (see Fig. 8).

Some research such as in [10] (Sanin, C. Sanderson, B. C. Lovell. 2012) presents various methods and algorithms for detection, removal of moving shadows as of 2012, and places them in a feature-based taxonomy that is made up of four categories, chromaticity, physics, geometry, and textures. The use of tracking performance is proposed as an approach to determine shadow detection

methods and algorithms. Of the most prominent methods are the method based on chromaticity is the fastest to implement and execute, but sensitive to noise and fails when the spectral properties of objects when these are similar to those of the background and the method based on textures of large and small regions where the results are more accurate, although its computational cost is high.



Fig. 8. Dataset Folder Structure.

Likewise, in [23] (D. Samaras, D. Metaxas. 2003) they present a method for the integration of nonlinear holonomic constraints in deformable models and its application to the problems of shape and direction estimation of the illumination source from hats. Their proposal indicates that it works when the direction of the light source is not known. They coupled the shape estimation method with a light estimation method were better shape estimation results in better light estimation and vice versa.

This research in [32] (Hoiem, D., Efros, A.A. and Hebert, M 2005) introduces a method that learns appearance-based geometric class models to estimate general geometric properties of scenes, even those that are cluttered and natural. These geometric classes define the three-dimensional orientation of regions of an image relative to the camera position. For robust estimation of the structure of a scene using a single image, the authors develop a multiple-hypothesis approach that also provides confidence measures for each geometric label.

These confidence measures have the potential to boost performance in a variety of computer vision applications. The paper not only provides a detailed quantitative evaluation of the algorithm using an exterior image data set, but also demonstrates the effectiveness of the technique in two specific practical applications: object detection and automatic scene reconstruction from a single view. The integration of geometric estimation into these processes evidences

how a thorough understanding of 3D geometry can be instrumental for advances in computer vision.

Likewise, in [18] (S. H. Khan, M. Bennamoun et al. 2014) they use multiple deep convolutional neural networks (ConvNets), where their architecture consists of alternating convolution and subsampling layers. This research is focused on shadow detection, having as input a database containing in various lighting conditions with sunny, cloudy and dark environments. For this, they used a Conditional Random Field (CRF) model, which translates into predictions for each pixel of each test image, and are subsequently compared with the actual shadow masks. This enforces labeling consistency across the nodes of a gridded graph defined on the image by eliminating isolated labeling results.

In [29] (Saxena, A., Sun, M. and Ng, A.Y. 2009) they introduce an algorithm for deducing three-dimensional structures from individual still images. This algorithm outperforms previous methods, generating 3D models that are more accurate and visually superior. The approach consists of modeling the position and orientation of homogeneous regions in the image, known as superpixels, through a Markov random field (MRF). Through supervised training, the algorithm learns to estimate the parameters of the planes based on features extracted from the images and considers the interconnections between different segments of the image. Maximum a posteriori inference (MAP) of the model is efficiently executed by solving a linear program.

Unlike other models that assume scene-specific structures, such as the assumption of vertical planes with respect to the ground by Delage et al. and Hoiem et al. this algorithm is not limited to such assumptions, allowing it to generalize effectively even to scenes with significantly non-vertical structures. As a result, self-contained and aesthetically convincing 3D models have been generated for 64.9 % of the 588 Internet images tested, in contrast to the 33.1 % success rate of Hoiem et al.

2. Distribution and Structure of the Dataset

For the organization of the dataset, these were grouped according to the height measurements and their geometric shape. The dataset is made up of geometric figures such as spheres, cubes and cylinders of different heights.

The measurements were taken in centimeters, which are then handled in units, in order to facilitate the reuse of the dataset in any other measurement system (see Fig. 9).

Initially two variables (features) were defined in the dataset, the first being the type of figure or shape and the second the height of the 3D object. Subsequently, three more variables are added to the existing ones, these are the shadow, the shadow length and the angle of the light source. These variables are

within the model and were used in the learning process to improve the accuracy of the model [28] (René, J. et al. 2023).

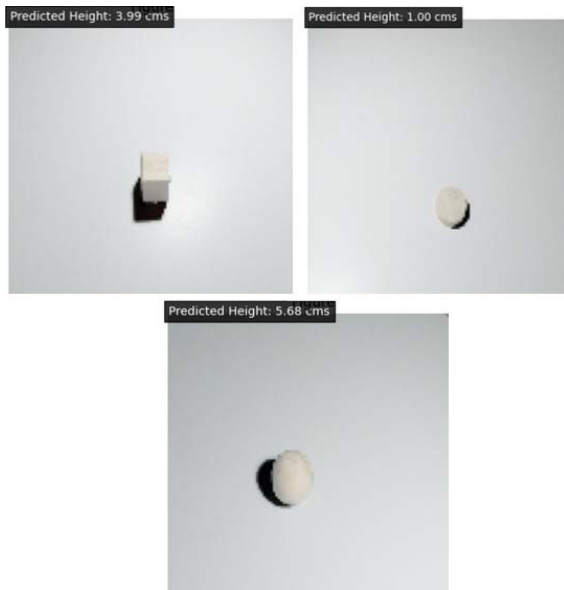


Fig. 9. Height Cylinder, Sphere and Cube.

3. Implementation and Analysis of Results

At the time of performing the network learning process, it is taken into account that it is distributed or divided into a training set (to build the model), a validation set (to test different parameters of the learning algorithm) and a test set (to evaluate the quality of the model). A suggested distribution of the data could be as follows, 80 % for the training set, 10 % for the validation set and 10 % for the test set. (Tables 2 and 3). Similarly, it could also be 70 %, 15 % and 15 % respectively.

Complementary metrics were incorporated in order to thoroughly evaluate the performance of the model throughout the training process. The model underwent training using the fit function and throughout this training period, the model's performance on the data set was continuously monitored.

Table 2. Dataset Distribution 1.

Dataset	Figures		Training	Validation	Test	Subtotal images
			80%	10%	10%	
Dataset No.1	Spheres	Spheres and Shadows	664			1.328
		Shadows	664			
	Cylinders	Cylinders and Shadows	190			380
		Shadows	190			
	Cubes	Cubes and Shadows	268			536
		Shadows	268			
Total images (100%)			2.245			2.245

Table 3. Dataset Distribution 2.

Dataset	Figures	Training	Validation	Test
Dataset No.2	Spheres	1.200	150	150
	Cylinders	1.200	150	150
	Cubes	1.200	150	150
Subtotal		3.600	450	450
Total images (100%)		4.500		
Dataset distribution		80%	10%	10%

This systematic monitoring allowed the necessary adjustments to be made to the model's hyperparameters, all with the aim of optimizing and enhancing its performance. It was trained with the dataset indicated above which allowed reaching an optimal performance on the test data and which was later validated with different data that determined its capacity to generalize new images.

The MAE value obtained is 0.24, which is interpreted to mean that on average, the model predictions have an absolute error of 0.24 units in the height prediction. In other words, on average, the model predictions deviate by 0.24 units from the actual height of the objects. Therefore, the MAE equal to 0.24 indicates the average size of the absolute errors in the predictions (see Fig. 10).

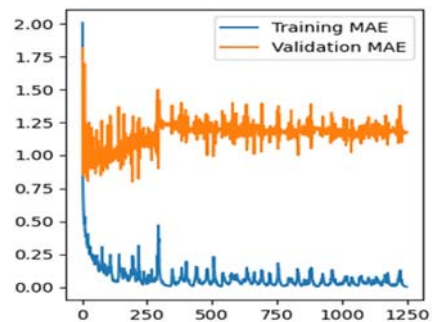


Fig. 10. Training and validation MAE for Height.

Evaluating the plot suggests that the model is learning correctly, but with room for optimization and improvement, since the model is learning as the training loss decreases over time (see Fig. 11). In the graph, the model is learning correctly, but with room for optimization and improvement, as the training loss decreases over time. It is observed that the validation loss function oscillates and, although it shows a decreasing trend, it remains relatively constant and fails to decrease at the same rate as the training loss function, which may indicate that the model has the ability to generalize to new data.

The value obtained for the MSE is 0.46 meaning that, on average, the square of the errors between the model predictions and the actual height of the shapes is 0.46. Thus, the MSE gives more weight to larger errors due to its quadratic nature. In this case, an MSE

value of 0.46 suggests that there is variability in the errors, including some errors that are larger and affect the average (see Fig. 12).

The coefficient of determination R^2 varies between 0 and 1, where 1 indicates that the model can explain all the variability in the data and 0 indicates that the model cannot explain any variability. A R^2 value of 0.929 is quite high, suggesting that the model has a good ability to explain the variability in the data.

In the tests, the Pearson correlation coefficient result is 0.8618 which is a high value and suggests that there is a strong positive linear relationship between the predictions and the actual values.

The structure of the training, validation and test dataset was structured in such a way that in addition to containing the images corresponding to each folder, it contains a flat file with the characteristics indicated above, such as the angle of the light source or the length of the shadow [28] (René, J. et al. 2023). The DataFrame structure has the following characteristics: image name (filename_image), figure name (name_figure), figure height(height_figure), shadow name (filename_image_shadow), shadow image name (name_image_shadow), shadow length (shadow_length), illumination angle (illumination_source_angle) (see Table 4).

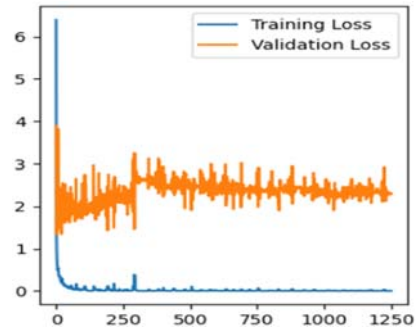


Fig. 11. Training and validation LOSS for Height.

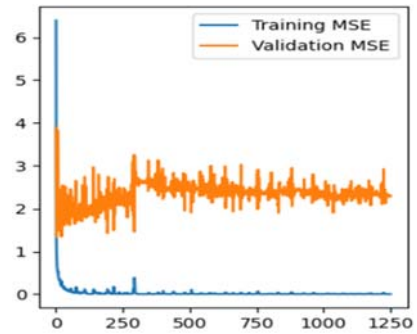


Fig. 12. Training and validation MSE for Height.

Table 4. DataFrame Structure.

filename_image(jpg)	name_image	height_figure cilindro(cm)	filename_image_shadow(jpg)	name_image_shadow	shadow_length	illumination_source_angle
cilindro1_00001G170	cilindro	1.0	cilindro1_00001G170s	sombra_cilindro	1.0	45
cilindro1_00001G180	cilindro	1.0	cilindro1_00001G180s	sombra_cilindro	1.0	45
cilindro1_00001G335	cilindro	1.0	cilindro1_00001G335s	sombra_cilindro	1.0	45
cilindro3_00001G180	cilindro	3.0	cilindro3_00001G180s	sombra_cilindro	3.0	45
cubo7_00002G335	cubo	7.0	cubo7_00002G335s	sombra_cubo	7.0	45
cubo8_00001G80	cubo	8.0	cubo8_00001G80s	sombra_cubo	8.0	45
cubo9_00001G335	cubo	9.0	cubo9_00001G335s	sombra_cubo	9.0	45
esfera1.5_00001G100	esfera	1.5	esfera1.5_00001G100s	sombra_esfera	1.5	45
esfera1_00001G190	esfera	1.0	esfera1_00001G190s	sombra_esfera	1.0	45
esfera2.5_00002G10	esfera	2.5	esfera2.5_00002G10s	sombra_esfera	2.5	45

The graph shows the learning curve of the model during the training and validation process, plotting the loss (error) as a function of the number of epochs, as the epochs advance, the training loss curve flattens, indicating that the model is reaching a convergence point where additional adjustments to the model weights and biases have a decreasing impact on the reduction of the training loss.

On the other hand, the loss on validation stabilizes and stays within a range with no clear trend to decrease with the passage of more epochs, suggesting that the model has learned as much as it can from the training data set given the current architecture and configuration (see Fig. 13).

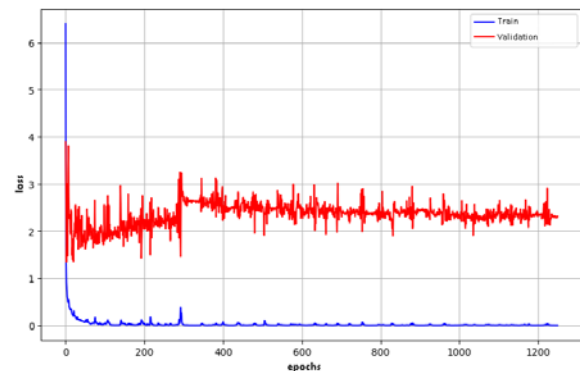


Fig. 13. Model learning curve.

4. Results and Discussion

Based on the plot the accuracy of the predictions varies over different values of actual height. For example, for real heights of around 2 to 6, the predictions are clustered around the trend line, indicating predictions with higher accuracy. Whereas, for true heights between 7 and 10, the predictions appear to be more widely dispersed, indicating lower accuracy in that range. On the other hand, predictions for actual heights of approximately 8 and 9 show considerable variability, with some points predicted well below the actual value. Despite the scatter and some significant errors, the overall trend follows the trend line, indicating that, in general, the model has some ability to predict height based on the inputs provided, albeit with a margin of error that can be substantial in some cases (See Fig. 14. Scatter plot: differences between actual vs. predicted height).

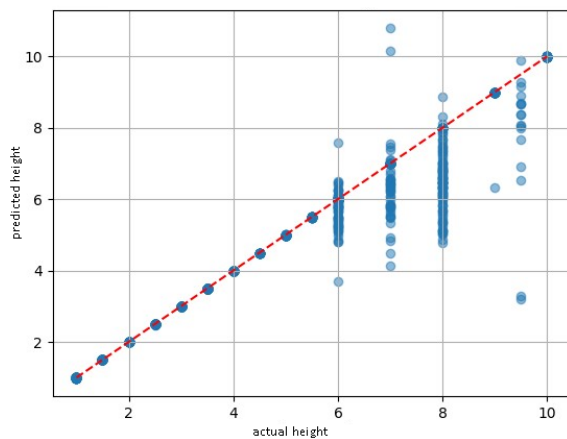


Fig. 14. Scatter plot: differences between actual vs. predicted height.

The histogram shows the distribution of the differences between the actual height and the height predicted by the proposed model. The x-axis represents the difference between the actual height and the predicted height, where negative values indicate that the predicted height was less than the actual height, positive values indicate that the predicted height was greater than the actual height, and a value of 0 would indicate an accurate prediction. On the other hand, the y-axis represents the frequency, or the number of times, that each height difference occurs. The plot shows a very high concentration of differences around 0, suggesting that most of the model predictions are very close to the actual height. This is indicative of good model performance on the height prediction task (see Fig. 15).

The box plot shows the distribution of prediction errors for three types of shapes: cylinder, cube and sphere used by the model. Analyzing the box plot shows that the model predicts the height of cylinders with low variability and good accuracy. On the other hand, for cubes, the accuracy is lower, and for spheres,

although most of the predictions are accurate, there is a significant amount of large overestimation errors (the model predicts a greater height than the actual height).

These differences may indicate that the model needs additional adjustments or training to improve its accuracy in estimating height, especially for figures that are spheres. Similarly, there are outliers, which are the points outside the whiskers. For cylinders, the model is consistent, as reflected in the small and symmetric errors around the median. Similarly, the median errors for the cubes are close to zero, suggesting accuracy in the predictions, and the median errors for the spheres appear to be the furthest from zero compared to the cylinders and cubes, suggesting a tendency to systematically overestimate or underestimate (see Fig. 16).

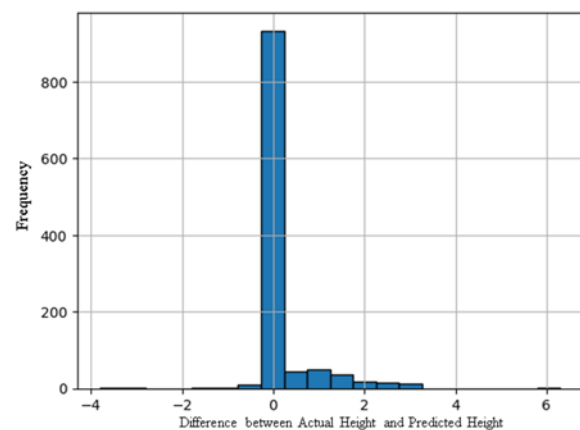


Fig. 15. Histogram of Differences between Actual Height and Predicted Height.

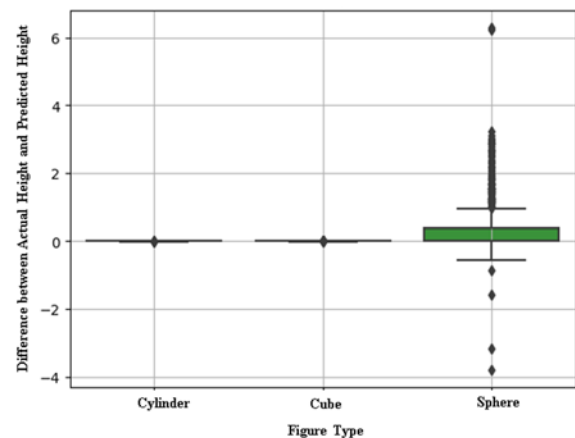


Fig. 16. Box Plot: Prediction Errors by Figure Type.

The residual plot for the model indicates a generally good fit, with consistently low errors for most samples. The plot shows data points with high residuals, which are an important source of information for improving the model; the residuals are

the difference between the actual values and the values predicted by the model for each sample (see Fig. 17).

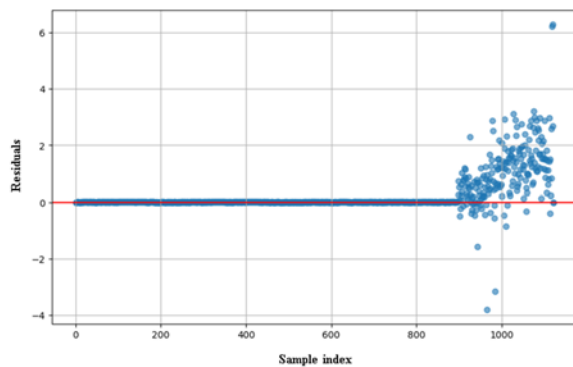


Fig. 17. Plot of residuals.

Cross-validation is a technique used to evaluate the generalizability of a model by training and evaluating it on different subsets of the original data set. In this case, a K-fold with $k = 5$ has been used, which means that the data has been divided into 5 subsets (folds). In each cross-validation iteration, the 4 folds are used to train the model and 1 fold is used to evaluate it. This process is repeated 5 times, each time with a different fold as the validation set. After applying cross-validation model C with 1.250 epochs, despite not having the most Epochs, outperforms the rest in terms of all metrics.

On this occasion, model C is the most outstanding in all aspects in terms of performance as well as MAE and MSE. If one were to choose a model based on these metrics alone, model C would be the choice (see Table 5).

Table 5. General results of the cross-validated model.

Model	Fold	Epochs	Loss	MAE (Mean Absolute Error)	MSE (Mean Squared Error)
Modelo A	1,2,3,4,5	600	0,625776678323745	0,516906213760376	0,625776678323745
Modelo B	1,2,3,4,5	800	0,640111273527067	0,640111273527067	0,640111273527144
Modelo C	1,2,3,4,5	1.250	0,542674350738525	0,483043521642684	0,542674350738525
Modelo D	1,2,3,4,5	1.600	0,571656787395477	0,486995190382003	0,571656787395477

The configuration is the same for the model, what changes is the number of epochs:

- Epochs: 1.250;
- Batch size: 32;
- Verbose: 1;
- Input shape: (128, 128, 3);
- Dataset: 2.244 images;
- $k = 5$: number of folds.

The model was evaluated at different epochs to determine how the number of iterations during training affects model performance. Increasing the epochs provided more opportunities for the model to learn patterns in the data, but there is also a risk of overfitting if the model is overtrained. Evolution shows that simply increasing the Epochs does not guarantee an improvement in performance. It is possible that after a certain point, more Epochs may lead to overfitting or may not bring significant improvements.

In this case, model C with 1.250 epochs has the best performance, indicating that it may be the optimal point in terms of trade-off between training time and model performance. The table shows us the cross-validation of four different models (model A, B, C and D) using 5 folds (the splits of the data for cross-validation). The results are averages of the metrics of those 5 folds (see Table 5).

The graphs represent the evolution of the performance of a machine-learning model over a number of epochs during training and validation in terms of three different metrics: the Mean Absolute Error (MAE), the Mean Squared Error (MSE) and the Loss function. The MAE and MSE metrics are regression measures that are quantifying the difference between the values predicted by the model and the actual values. The graphs show that after the first few epochs, the validation metrics (green lines) stabilize, indicating that the model is learning effectively without improving significantly after a certain point. This stabilization suggests that the model has reached its generalization ability with the validation data. In addition, the closeness between the training and validation lines on all metrics indicates that the model has consistent behavior between the training and validation data. There is no large gap that would indicate significant overfitting.

MAE values range from approximately 0.42 to 0.53, suggesting that, on average, model predictions deviate from actual values by this margin. The MSE values vary similarly to the MAE, and since the MSE penalizes larger errors more, the relatively low magnitude of these values suggests that there are no extremely large errors that are significantly affecting performance. The loss function values reflect the MSE

and are aligned with the MAE, confirming consistency in the model's performance assessment. In summary, the model performs acceptably consistently and stably throughout the validation. There are no obvious signs of overfitting and the model generalizes well to data not seen in the cross-validation. The numerical values and plots indicate that the model is reliable on different data sets, which is a desirable feature in a machine-learning model (see Figs. 18-20).

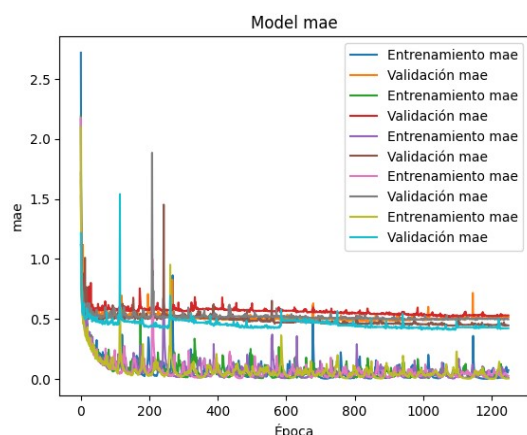


Fig. 18. Average performance in cross-validation: MAE.

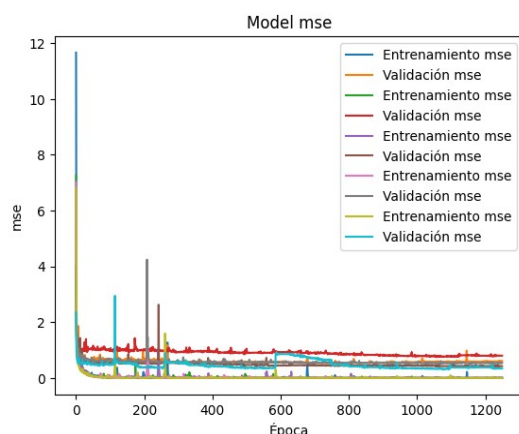


Fig. 19. Average performance in cross-validation: MSE.

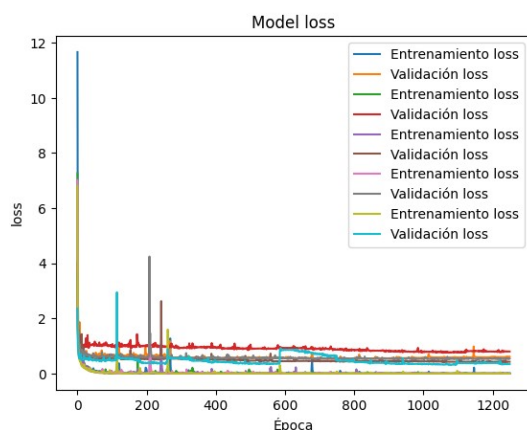


Fig. 20. Average cross-validation performance: Loss.

5. Conclusions

The areas of highest accuracy are located in the lower to middle range of true heights, where the clustering of points around the trend line suggests more reliable predictive performance. Similarly, the model can be optimized for height prediction. Optimization could include exploring more complex network architectures, incorporating regularization techniques to mitigate overfitting, making the dataset more diverse in shapes or figures and shadows.

The model seems to generalize well the relationship between the inputs and the height of the target figure. This is apparent from the histogram of differences between actual and predicted height, which shows most of the differences clustered near zero. The predictions are close to the actual values in most cases, as evidenced by the residual plot, where most of the points are close to the residual zero line.

Machine learning models are rarely complete. There is always room for improvement. Therefore, it is considered important to incorporate more data, test different neural network architectures, and even combine multiple models into one ensemble to improve performance. Also include new data for a more diverse dataset, since the quality and quantity of training data can have a large impact on model performance.

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Classifying Musical Instrument Using Spatiotemporal Features with Deep Neural Networks

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Abstract: Similar to trained human ears, a machine could be trained to recognize musical instruments presence in audio tracks for the purpose of musical information retrieval. The audio signal produced by an instrument has unique temporal and spectral features, which could be extracted for machine learning purpose. This research investigates the use of spatiotemporal features, which were converted from temporal and spectral features of monophonic music for this application. The performance of a recurrent neural network model called bidirectional Long Short Term Memory (Bi-LSTM) network and two convolutional neural networks (CNNs) in musical instruments classification with log Mel-spectrogram were analyzed and evaluated. With a dataset of 14 musical instruments, the Bi-LSTM and 1-dimensional CNN models obtained a macro F1 score of 0.976 and 0.977 respectively, while 2-dimensional CNN model achieved 0.985.

Keywords: Long Short-Term Memory Network (LSTM), Convolutional Neural Network (CNN), Musical instruments classification, Mel-Spectrogram, Spectral features, Spatiotemporal features.

1. Introduction

This paper is an extended version of the ASPAI '2023 conference paper published in June 2023 [1]. Musical instrument recognition is an active research area in the music information retrieval (MIR) field and it has contributed significantly in providing essential and useful information for various audio or music applications. Some examples are playlist generation, music recommendation system, music browsing, music transcription, and genre classification. Compared to text search with its input queries and data are both in text format, music search is a more complex task as the music files are in digital format. Hence, it is imperative to convert music information into text format, i.e., music tags, to facilitate music search. Musical instrument recognition plays an

important role to provide instrumental information in music search with the increase of digital music files. Automatic music transcription and playlist generation in music streaming platforms rely heavily on MIR tasks to provide better users experience.

Audio information extraction is a challenging task, especially from polyphonic music that includes human voice. The task of musical instruments identification in polyphonic music with multiple musical instruments requires a complicated system, as the sound generated by different instruments may varies in timbre, instrument quality and playing style, not to mention the overlapping of sound from multiple instruments. Various forms of convolutional neural network (CNN) approach using spectral and cepstral features have been widely used and have shown a better performance over the traditional machine

learning approach. However, MIR is intrinsically a temporal task and some past literatures have indicated that temporal features provide important information as well in musical instrument classification [2]. It is necessary to develop an effective model on processing temporal information and learning from time series data, i.e., music. In this paper, a temporal model is developed and its performance compared to two commonly employed neural networks using cepstral features.

2. Prior Work

Recent developments in musical instrument classification involve the use of machine learning and deep learning using neural networks. As music is a form of audio signals that varies with time, conversion from its temporal to matrix-like format in order to match the inputs requirements to any neural network is necessary. This conversion process involves the selection of important features in the audio signals. Generally, the audio features are divided into physical features and perceptual features [3]. The former includes measurable temporal and spectral features, e.g., the zero crossing rate, the energy function, the spectrum, while the latter refers to subjective terms such as relative loudness, brightness, pitch and timbre.

Based on the literature reviewed, the performance of the classification systems depends on the features selected, the classifier used, and the number of and the family of musical instruments trained. This section discusses the first two aspects, while keeping the third aspect in consideration, followed by some review on instrument identification in monophonic and polyphonic music pieces.

2.1. Feature Selection

In order to recognize a particular instrument, the unique characteristics of the musical notes played by the instrument ought to be properly selected.

Among the many features extraction methods, wavelet transform coefficients, Mel-spectrogram, Linear Frequency Cepstral Coefficients (LFCCs), Mel-Frequency Cepstral Coefficients (MFCCs), Perceptual Linear Prediction (PLP), are commonly used in musical instrument recognition.

Both continuous and discrete wavelet transforms convert the audio signal into time-frequency domain for the extraction of features such as instantaneous frequency, pitch and sub-band energies from wavelet coefficients. One of the significant work using wavelet is [4]. Evaluation on 13 instruments using 3 significant features of log Scale Distribution Width (SDW), Time Variance of Dominant Scale (TVDS) and Wavelet Mean of Inverse Scale (WMIS) achieved an accuracy of 85.5 %. A simple classifier called linear discrimination analysis (LDA) classifiers with leave-one-out cross-validation method was employed in

their work. Subsequent work done by Kothe et al [5] in comparing the performance of wavelet features with temporal features, spectral features, cepstral features and a combination of all features showed that wavelet features performed better than others using SVM classifier. Their work also demonstrated that best performance could be obtained by using a smaller number of features with proper weight.

Various forms of spectrogram have been adopted by researchers in training intelligent systems. Huaysrijan and Pongpinigpinyo [6] compared the performance of Mel-spectrogram and MFCCs in recognizing 13 Thai classical instruments with CNN. MFCCs marginally outperformed Mel-spectrogram by 1 % in both accuracy and F1 score at 0.99. They also compared the performance of 3 deep neural network, namely CNN, LSTM (Long Short-Term Memory) and CRNN (Convolutional Recurrent Neural Network), in which CNN ranked top at 99.44 %, LSTM at 81.42 % while CRNN at 93.35 % accuracy. In another work, log Mel-spectrogram was used as acoustic features by Yun and Bi [2] in comparing the performance of LeNet (a form of CNN) and LSTM in recognizing 14 instruments. Again, LeNet was slightly better than LSTM with an accuracy of 0.83 versus 0.82. Szeliga et al [7] also used Mel-spectrograms in their work on staged training a CNN in musical instrument recognition. Both monophonic and polyphonic data of 7 instruments were used. The accuracy is lower at about 75 %. This is expected as the identifying the predominant instrument in polyphonic music is a big challenge.

Many have used MFCCs, either alone or together with other features in musical instrument classification [6, 8-15]. Mahanta et al. [8] used the MFCCs obtained from the audio data of 20 instruments belonging to 4 families viz. woodwinds, brass, percussion, and strings to train an Artificial Neural Network (ANN) with Rectified Linear Unit (ReLU) activation function and ADAM optimizer. A high accuracy and F1 score of 0.97 was reported. In their work on comparing 4 feature extraction methods, Rodin et al [9] discovered that MFCCs did extremely well in classifying 15 classes of instruments using two types of CNN. ResNet-34 models that were trained using Mel-Spectrograms, MFCCs and LFCCs achieved a perfect accuracy of 100 %, while VGG-16 models obtained 100 % accuracy using MFCCs while Mel-Spectrograms 99.72 % and LFCCs 99.44 %. Masood and Shadab Khan [10] used MFCCs with 7 timbre features to train an ANN on classifying 4 instruments, i.e., violin, piano, flute, drum and guitar, yielded an average accuracy of 89.17 %. A long training time of 450 epochs was reported.

2.2. Classifier

The types of classifiers used in musical instrument recognition basically fall into two categories: machine learning classifiers, e.g., K-Nearest Neighbour (KNN) [5, 12], Support Vector Machine (SVM) [5, 16-18],

Hidden Markov Model (HMM) [11, 18]; and neural network classifiers, e.g., ANN [8, 13, 19, 20], CNN [2, 6, 7, 9, 15, 16, 21-23] and LSTM [2, 6].

Bhalke et al [12] used 39 MFCC features to recognize 6 Indian musical instruments namely piano, guitar, violin, synthesizer, harmonica and accordion using KNN obtained an average accuracy of 91.83 %. Joder, *et al* [18] employed a combination of 13 MFCC features and other specially selected temporal and spectral features to classify 8 instruments: piano, guitar, oboe, clarinet, French horn, trumpet, cello and violin achieved an average accuracy of 84.5 % using SVM. In their work on evaluating the performance of 3 feature extraction techniques and 3 classifiers on 4 dissimilar instruments, Jeyalakshimi, *et al* [11] reported that MFCCs and HMM gave the best accuracy of 90.5 %.

Between machine learning classifiers and neural network classifiers, neural network classifiers were more widely used and performed better. Various forms of CNN were able to achieve more than 90 % accuracy with MFCCs features in monophonic musical instrument [2, 6, 7, 9, 15] and mixed results in predominant instrument identification in polyphonic music [22-25] using various dataset.

2.3. Instrument Recognition in Monophonic Music

For musical instruments recognition in monophonic music, Toghiani-Rizi and Windmark, [19], collected audio samples from the London Philharmonic Orchestra dataset and converted them into frequency domain signals. The authors trained an artificial neural network (ANN) model and carried out experiments analyzing the effect of different audio signal features on recognition accuracy – the whole audio sample, only the attack of audio signal, all characteristics of signal except attack, the first 100 Hz of the signal in frequency domain and the following 900 Hz of the same spectrum. The results showed that the ANN model with complete music sample reached the highest average accuracy of 93.5 % among the experiments.

Chakraborty and Parekh, [13], extracted 6 audio descriptors including Mel Frequency Cepstral Coefficients (MFCC), linear predictive coding (LPC), cepstral coefficients (CC) and spectral centroids as spectral descriptors, pitch salience and hierarchical clustering on principal components (HPCP) as tonal descriptors. All the features respectively acted as inputs to 4 different classifiers, namely, k-nearest neighbour (k-NN), support vector machine algorithm (SVM), ANN and random forest. As a result, the ANN classifier showed the best performance with better tuning. Meanwhile, CC was considered the best approach among other features, even the regular approaches with MFCC.

In [20], the authors introduced the implementation of an ANN-based model with specific transient length selection which contained most significant music information. Two experiments were carried out on string instruments recognition where the first experiment had applied the first 1000 Hz normalized frequency spectrum with selected onset position as input data and achieved an accuracy of 96.47 %. As for the second experiment, the authors had extended the signal attack length which included signal peak amplitude that carried more fundamental information, resulting in the final accuracy of 98.22 %.

Kakarwal and Chaudhary [26] proposed a k-NN model on classifying different Indian string instruments by analyzing features of audio samples including zero crossing rate (ZCR), roughness, spectral centroid, brightness and roll-off. The research claimed that the average accuracy of the classifier with the combination of more than 3 audio features was much higher than that with only a single feature extraction, which are 90 % and 67 % respectively. It showed that the advantages of audio feature extraction involving multiple temporal and spectral features is to provide sufficient music information retrieval.

With the motivation from previous LSTM-based tasks, Yun and Bi, [2], implemented a single layer (LSTM) network on the task of musical instruments through temporal features extraction of audio signals. Like CNN approach, the authors trained the LSTM model with log Mel-spectrogram but with temporal features. The LSTM model was then compared with a LeNet CNN model on the performance of instrument recognition and both models obtained the accuracies of 81.85 % and 83.04 % respectively, which were pretty close.

2.4. Instrument Recognition in Monophonic Music

In the topic of polyphonic musical instruments identification and analysis, Han et al. [24] had done notable works exploiting a convolution neural network (CNN) model with Mel-spectrogram as structure input on instrument recognition. The authors had also proposed a t-distributed stochastic neighbor embedding (t-SNE) visualization to show clustering results of each convolutional block. By demonstrating comparison with SVM, the conventional algorithm, Han et al.'s proposed model with CovNet structure had shown better performance with higher micro and macro F1-measure – 0.619 and 0.513 respectively. However, due to imbalance in sample sizes for each instrument type, there was low identification on cello and clarinet in instrument recognition on IRMAS dataset.

Using Han et al.'s research as baseline, Yu et al., [23], introduced a CovNet-ABC model where implementing a CNN model embedded with auxiliary classification based on instrument grouping, batch normalization and center loss. With the help of

auxiliary classification, the problem of poor identification on cello and clarinet presented in [8] had been minimized. As a drawback, some instruments belonging to the same instrument family such as saxophone and trumpet had increased the classification difficulty due to overlapping and great similarities. Anyhow, the model performance with 0.685 micro F1-measure and 0.597 macro F1-measure had shown a slight improvement over [24].

By using the aforementioned IRMAS dataset, Solanki and Pandey, [25], proposed a CNN model with ALEXNET structure containing 8 convolutional layers with learnable parameters to fit large datasets. The proposed model had implemented a 2-dimensional (2D) convolutional neural network with varying filters on instrument recognition. Similar to [24], input audio signals were converted into the form of Mel-spectrogram whilst rectified linear unit (ReLU) activation, max-pooling and dropout regulation were applied to the proposed model. As the results presentation, SoftMax function was utilized to identify the posterior accuracy of musical instruments classification. With the dropout of 0.2, the proposed model achieved an excellent result with 92.80 % accuracy, yet during training and testing period, overfitting occurred during 55th and 56th epoch from a total of 60 epochs. Additionally, a comparison was made between the ReLU and leaky ReLU activation function, as a result, the ReLU activation performed better with accuracy of 92.61 %.

Besides, with the same dataset, IRMAS, Racharla, *et al.*, [17], proposed an approach to classify predominant musical instruments from polyphonic music based on spectral features. In this paper, traditional classification algorithms were implemented including decision tree, Logistic Regression, Light BGM, XG Boost and Random Forest. Additionally, the machine learning technique, SVM, was applied as well to extract MFCC and spectral features inclusive of ZCR, spectral centroid, bandwidth and roll-off. As an outcome of the research and comparison, recognition model with SVM algorithm yielded the highest accuracy of 76 % over the traditional classification approaches. Nonetheless, Racharla *et al.* had shown the effectiveness of multi-spectral features extraction on the improvement in classification accuracy.

Distinctively, Gururani *et al.* [22], proposed an approach to detect music instruments activity in polyphonic music on a close-grained temporal scale instead of focusing on predominant instruments prediction in a given audio sample as per other works. For auto generation of annotations for instrument activity, the authors picked multitrack audio from MedleyDB and Mixing Secrets over the IRMAS dataset used in past related works. The reason behind was that manual annotation in IRMAS dataset might contain more errors and IRMAS consisted of only a single instrument in each track which might be unideal for instrument activity detection. In their work, 3 different deep neural networks (DNNs) models: multilayer perceptron (MLP), convolution neural

networks (CNN), and convolution recurrent neural networks (CRNN) were proposed and compared. The performance of models was summarized using area under curve (AUC) presentation and it was presented that both the CRNN and CNN outperformed MLP algorithm in 18 instruments detection.

In the subsequent year, instead of strongly labelled data, Gururani *et al.*, [27], chose weakly labelled data in the OpenMIC dataset containing 20 distinct musical instruments for instrument recognition. The authors had compared an attention-based model against the other 3 baseline classification models including binary relevance random forest (RF_BR), recurrent neural network (RNN), and fully connected neural networks (FCNN). Undoubtedly, the model incorporating attention mechanism had shown an overall improvement in classification performance where the model attended to specific time intervals in the track associated with each instrument, resulting in interpretable results.

Motivated by these past researchers, this paper explored the performance of a LSTM network and two convolution networks in recognizing musical instruments in monophonic music taken from a standard dataset. With the intent of improving its performance, the spatiotemporal features, in the form of log Mel-Spectrograms of the audio data, were used for training and testing.

3. System Architecture

The research framework is illustrated in Fig. 1. Pre-labeled monophonic audio samples were first preprocessed before the audio tracks were converted into their corresponding Mel-Spectrograms. The Bi-LSTM and CNN models were developed and trained using these Mel-Spectrograms. Training and validation losses were then used to tune the model parameters until an optimum performance was obtained for each model. The performance of these trained model was then evaluated on a new set of testing data and the results compared.

The dataset used in this project was extracted from monophonic audio samples in Kaggle dataset developed by Dibakar Sil [28]. The audio samples of 14 instruments from the family of string, woodwind and brass were categorized into different subfolders annotated with the instrument name. Due to the quantity of audio tracks available in the dataset is different for each instrument, uneven number of samples were used in this study. The distribution of these instruments are shown in Fig. 2. Violin occupies the highest number of samples of 278 while viola the lowest at 108 in the training and validation dataset. Similarly, the quantity of samples in the testing dataset follow the proportion, with the former high at 100 while the latter lower at 50.

The models built for evaluation are Bi-LSTM, one-dimensional CNN (1D CNN) and two-dimensional CNN (2D CNN).

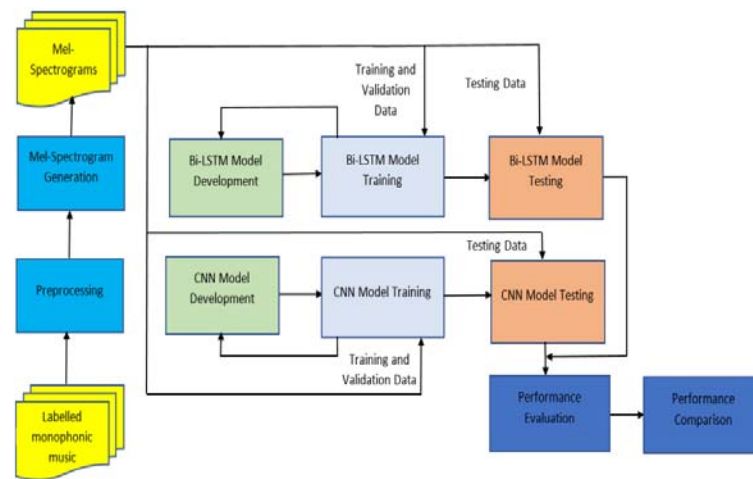


Fig. 1. Proposed research framework.

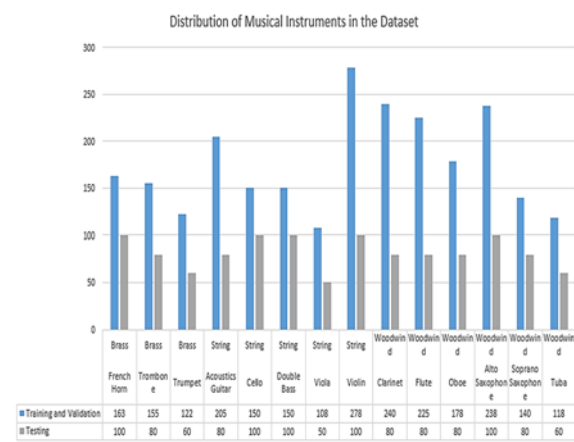


Fig. 2. Distribution of musical instrument audio samples.

3.1. Audio Signal Preprocessing

The process of extracting spatiotemporal features in the form of a log Mel-spectrograms from the audio data is illustrated in Fig. 3. The audio samples in 16-bit WAV format were first enveloped to remove silence in order to avoid the problem of every audio clip having similar patterns. Then each clip was trimmed into pieces of 1 second to form the actual input data. Consequently, the total number of audio clips for training and validation was 2470 clips of audio signal of equal length, in which 80 % was used for training and 20 % for validation. A fresh set of data was prepared in a similar manner for testing.

The trimmed audio clips were down-sampled with a rate of 22050 Hz which was the Nyquist rate, and the stereo audio was converted into mono input by taking the average of the left and right audio channels. The sampling rate of 22050 Hz allows the use of up to 11025 Hz as Nyquist frequency which can include most of the instrument information. Noises above the frequency range were removed.

In this research, a Mel-spectrogram was used as the time-frequency represented input data to the system

and hence the implementation of short-time Fourier transform (STFT) with 512 sample length was introduced. Each of the 1-s audio signals was further divided into short term sequences of fixed window size of 25 ms and a hop size of 10 ms, and then the fast Fourier transform (FFT) was applied on the signals. This approach is similar to that proposed by S. Rajesh and N. J. Nalini [30].

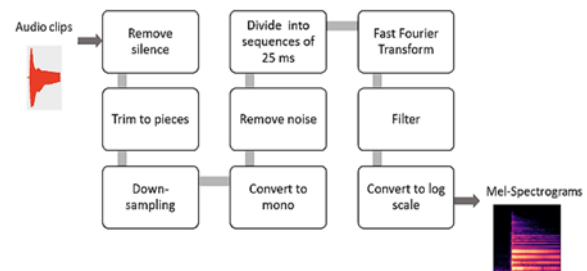
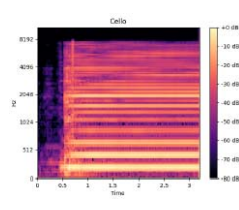
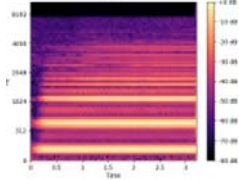
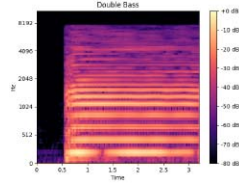
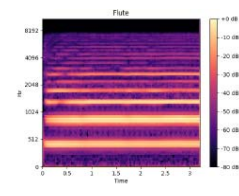
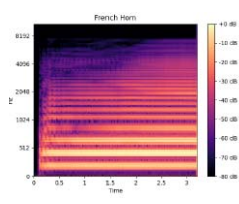
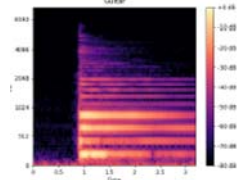
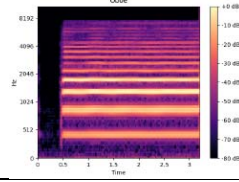
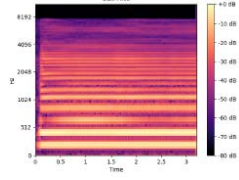
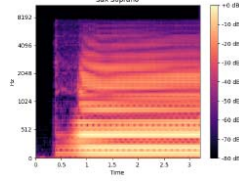
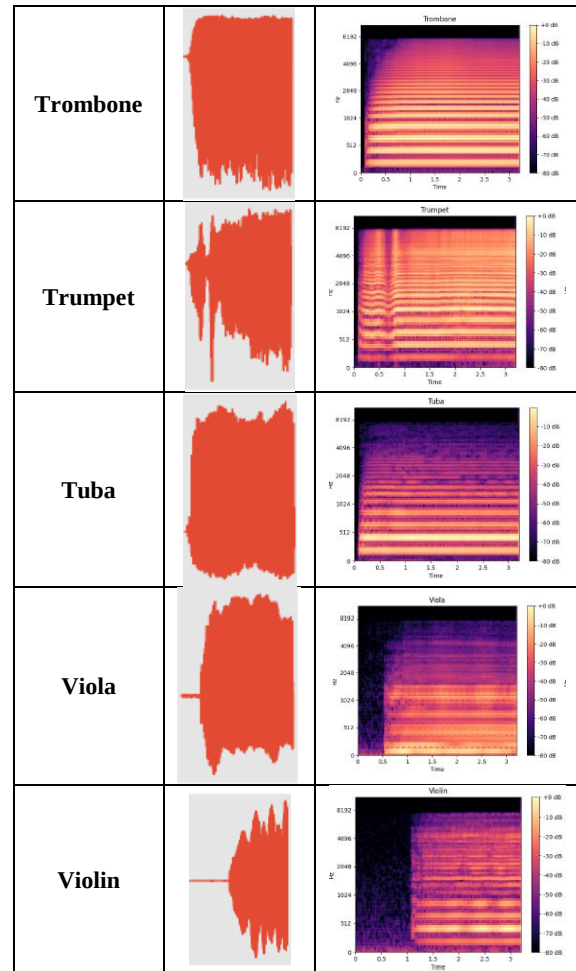


Fig. 3. Audio signal pre-processing and Mel-Spectrogram generation.

In the spectrogram of the audio signal, where the frequency axis is linear, the higher harmonics were not equally represented as the lower harmonics, in which the same differences in low frequencies are perceived as bigger differences in high frequencies. Furthermore, due to the nonlinearity of the human audio perception, where the pitch and loudness are logarithmic in nature, the frequency and the intensity that represent the loudness of the signal were converted into logarithmic scale. Hence, the corresponding Mel-spectrograms were generated by using a Mel filter-bank with 128 bands to reduce the dimensionality of the spectrogram generated, as suggested by [24]. The Mel-spectrogram was then converted into logarithmic scale for better audio visualization. The waveforms and the log Mel-spectrograms of the instruments used are illustrated in Table 1.

Table 1. Waveforms and Mel-Spectrograms of the instruments.

Instrument	Waveform	Mel-Spectrogram
Cello		
Clarinet		
Double Bass		
Flute		
French Horn		
Guitar		
Oboe		
Sax Alto		
Sax Soprano		



There are 3 axes in the Mel-spectrogram. The x-axis is the time; the y-axis is the frequency while the z-axis is the intensity of the audio signal in colour. It can be perceived as the representation of the audio signal in image form. A single point in the image conveys information on single frequency component of the audio signal and its corresponding strength at a specific time. Sliding across the horizontal axis, the temporal features, i.e., the fluctuation in the signal strength for all frequency components as time changes, can be observed; while sliding along the vertical axis reveals the spectral features that represent the variation in the composition of the signal at certain time. With the signal strength and frequency being depicted in logarithmic scale, forms the cepstral features, which can be viewed as time-varying patterns on the Mel-spectrogram, hence the term spatiotemporal features. The conversion of audio signal into image form enables the audio signal to be analyzed as an image and eases the utilization of any AI techniques that work on image. The resultant image size is 128×130 pixels.

3.2. Network Architecture

The models of the three neural networks were implemented using the Kapre (Keras Audio Preprocessing) library developed by Choi et al [29].

3.2.1. Bidirectional Long Short-term Memory (Bi-LSTM) Architecture

In this research, the Bi-LSTM model was implemented with two dense layers in a bidirectional manner, as illustrate in Fig. 4. The audio data was first normalized before going through the actual Bi-LSTM model, a time distributed dense layer was created to filter out the signal feature over time from the input data. Next, a bidirectional layer was constructed to compute the gradient in both forward and backward manner. The output from the bidirectional layer was then concatenated with the features filtered from the previous time-distributed dense layer.

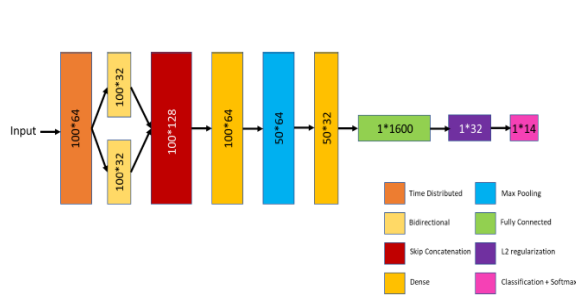


Fig. 4. Architecture of Bi-LSTM.

By doing so, the Bi-LSTM network could not only learn the signal features from the input data but also took reference in the concatenated features from these two layers. Subsequently, two dense layers with ReLU activation were created with a max-pooling layer in between to summarize the features from the first layer by calculating its maximum value. Since The Bi-LSTM was prone to overfitting, according to [30], a dropout of 0.5 was added before the classification layer to minimize the problem. On the classification layer, a SoftMax function was used to indicate the probability for each instrument.

3.2.2. 2D CNN Architecture

A simple 2-dimensional convolutional neural network (2D CNN) model similar to that of computer vision-based approaches like VGG-Net structure was constructed. The Mel-spectrogram formed the input data to the 5 layers CNN model. First layer was the hyperbolic tangent (tanh) convolution layer with a kernel size of 3*3 to learn the small features of data. The kernel size was maintained in the following convolution layers and the number of filters in each layer was increased by a factor of 2 for every two convolution layers to obtain the more specific information of the data as illustrated in Fig. 5. The structure is leaner than VGG16.

Zero padding was applied on the input data for each convolution layer to prevent the loss of some useful information with the increase of convolution layers. Also, a max-pooling method was used after

each convolution layer to compute the maximum value of the feature for each patch. However, after the last convolution layer, a global max-pooling layer was constructed to obtain the maximum value of all features before the fully flattened connected layer. After that, a dropout layer was added with the dropout rate of 0.3 as a slight improvement over [25] and eventually a SoftMax function was used for the classification layer. The reason not to use sigmoid function like in [24] is because there was only one instrument presented in each file in this research while sigmoid function was frequently used to handle multiple instruments classification.

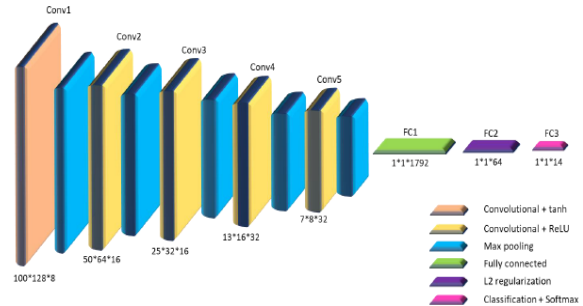


Fig. 5. Architecture of 2D CNN.

3.2.3. 1D CNN Architecture

A 1-dimensional convolutional neural network (1D CNN) was constructed with reference from [21]. The model had 5 time-distributed convolution layers which was the same number of layers as the 2D CNN model. With the time-distributed layers, the model would learn only the temporal features from the Mel-spectrogram. According to the authors, the small convolutional filters with the size of 3 gave the best accuracy. Hence, the kernel size for each convolutional layer was fixed at 3. The number of filters in each layer was increased by a factor of 2 for every layer as presented in Fig. 6. A 1D max-pooling layer was added after each convolution layer for maximum value computation from the previous layer. Similar to the 2D CNN model, a dropout layer was added before the classification layer and SoftMax function was integrated.

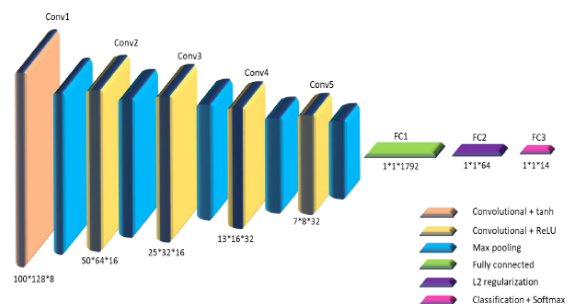


Fig. 6. Architecture of 1D CNN.

3.3. Performance Evaluation

The performance of the models was evaluated through predictions on new audio files taken from the same dataset. To determine accuracy on instrument recognition, the predicted results were visualized in a confusion matrix. The values of True Positive (TP), False Positive (FP), True Negative (TN) and False Negative (FN) were used to compute the overall accuracy, precision (P) and recall (R) of the model using (1) to (3). Following the evaluation method widely used in the past literature [24], the $F1$ score in (4) was used to obtain the overall performance of the model, which was the harmonic mean of precision.

$$Accuracy = \frac{TP+TN}{Total\ Predictions}, \quad (1)$$

$$P = \frac{TP}{TP + FP}, \quad (2)$$

$$R = \frac{TP}{TP + FN}, \quad (3)$$

$$F1 = \frac{2 \times P \times R}{P + R} \quad (4)$$

In addition, as the dataset used was multi-class labels with non-uniform distribution, macro-average computation and micro-average computation were carried out. The macro P and R scores were obtained individually for each class before the calculation of macro P_{macro} and R_{macro} , as illustrated in (5) and (6), where k is the total number of classes. $F1_{macro}$ was then computed using P_{macro} and R_{macro} , as shown in (7).

$$P_{macro} = \frac{\sum_{i=1}^k P_i}{k}, \quad (5)$$

$$R_{macro} = \frac{\sum_{i=1}^k R_i}{k}, \quad (6)$$

$$F1_{macro} = \frac{2 \times P_{macro} \times R_{macro}}{P_{macro} + R_{macro}} \quad (7)$$

On the other hand, the precision and recall score for micro-average were calculated individually from TP , TN , FP and FN of each instrument class. The micro precision (P_{micro}) was obtained from the sum of TP s for all the classes divided by the sum of all TP s and FP s. As for the micro recall score (R_{micro}), it would be the division of the total TP s for all the classes by the sum of TP s and FN s. Micro $F1$ score was then computed using P_{micro} and R_{micro} . The equations to compute them are given in equations (8) to (10).

$$P_{micro} = \frac{\sum_{i=1}^k TP_i}{\sum_{i=1}^k TP_i + FP_i}, \quad (8)$$

$$R_{micro} = \frac{\sum_{i=1}^k TP_i}{\sum_{i=1}^k TP_i + FN_i}, \quad (9)$$

$$F1_{macro} = \frac{2 \times P_{macro} \times R_{macro}}{P_{macro} + R_{macro}} \quad (10)$$

With the overall accuracy and $F1$ measure obtained, a comparison was made among the Bi-LSTM model and the CNN models in musical instrument classification based on monophonic audio signals.

4. Results and Discussions

All three trained models were able to achieve validation accuracy of 1 after 30 epochs of training. It is worth to note that 2D CNN achieved the best accuracy as early as the 8th epoch, whereas the Bi-LSTM model only managed its best accuracy on the 12th epoch. However, it was unstable and fluctuated before stabilizing on the 24th epoch. The 1D CNN model took the longest time to achieve a stable best accuracy on the 29th epoch. These can be seen in Fig. 7.



Fig. 7. Training accuracy.

4.1. Predictive Performance of Models

A new set of data was prepared for the musical instruments prediction to examine the practical performance of the three models. The test results are illustrated in Fig. 8. All the three models produced very similar accuracies. In the macro computation of accuracy, precision, recall and $F1$ score, the predictive accuracy of Bi-LSTM is the same as the 1D CNN model of 0.997 while the overall accuracy of the 2D CNN model is 0.998.

The macro precision of Bi-LSTM and 1D CNN are similar at 0.977 while 2D CNN is slightly better at 0.987. However, the macro recall of Bi-LSTM is the

worst at 0.975, 1D CNN is marginally better at 0.978 while 2D CNN is the winner at 0.984. The macro F1 score in ascending order is therefore Bi-LSTM at 0.976, 1D CNN at 0.977 and 2D CNN at 0.985.

The micro precision, recall and F1 score of the 3 models follows the similar trend in macro with 2D CNN performing the best while Bi-LSTM the worst with a small difference 0.01 or 1 %.

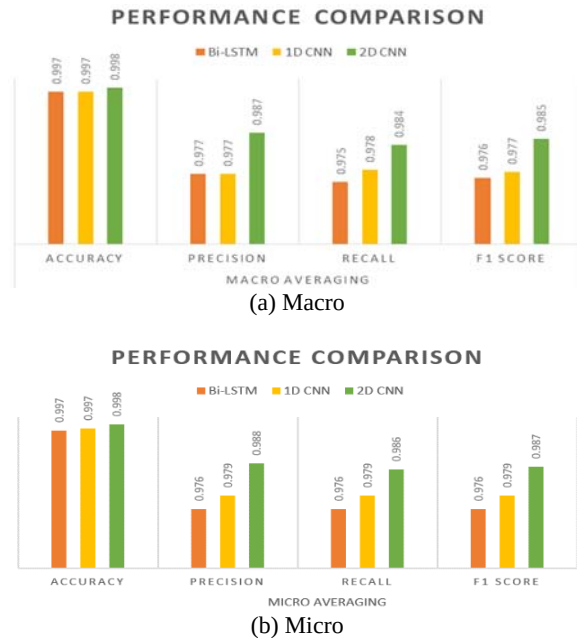


Fig. 8. Overall performance.

A deeper analysis into the performance of each model revealed the difference between micro and macro precision is larger than the differences between the micro and macro values in recall and F1 score in Bi-LSTM, as shown in Fig. 9(a). This suggests there could be more false positives in at least one of the instruments in this model. Interestingly, looking at Fig. 9(b) and Fig. 9(c), 1D CNN and 2D CNN exhibit the opposite trend, i.e., the micro results are better than the macro, implying that these two models perform more consistently across all the instruments as compared to Bi-LSTM. This led us into analyzing the instrument-wise performance of these 3 classifiers.

4.2. Performance on Instrument-wise Identification

Fig. 10 shows the predictive performance of Bi-LSTM in all 14 instruments in the form of a confusion matrix while Table 2 summarizes the accuracy, precision, recall and F1 score of all the instruments.

Bi-LSTM performed the best on cello and trombone with an accuracy and an F1 score of 1 and the worst in sax soprano with the lowest F1 score of 0.91. The low F1 score is mainly attributed by the low

precision of 0.833 caused by high false positive (FP) where the model wrongly predicted 12 cases of violin and 1 case of flute, French horn, trumpet and tuba each as sax soprano. The model is found to perform poorly on violin in recall due to high false negative with 12 cases wrongly predicted as sax soprano mentioned above. The model was found to confuse between sax soprano and violin, probably due to some similarity between the Mel-Spectrograms of these two instruments in some musical notes.

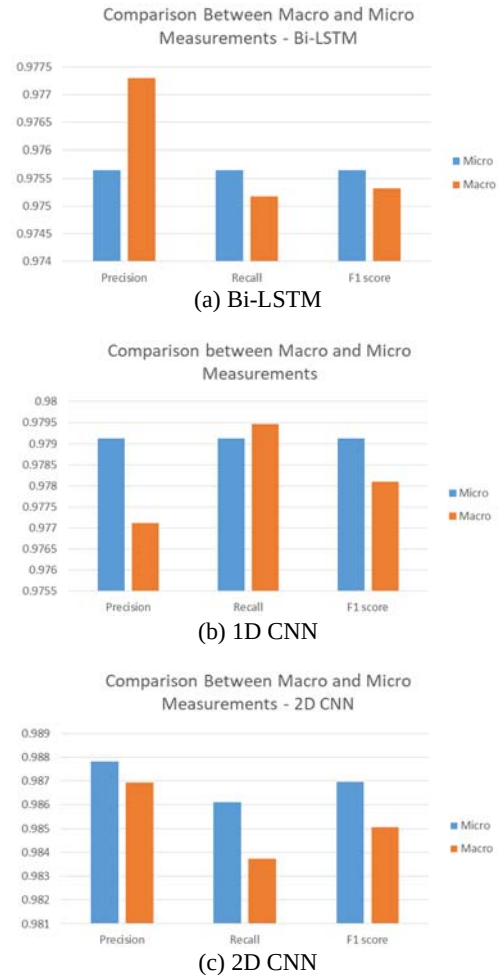


Fig. 9. Results of macro and micro measurements.

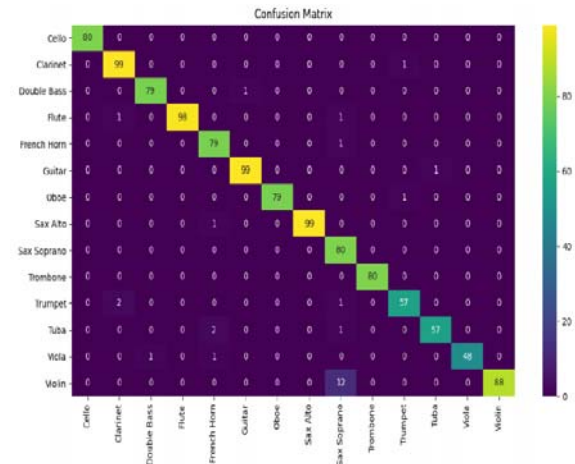
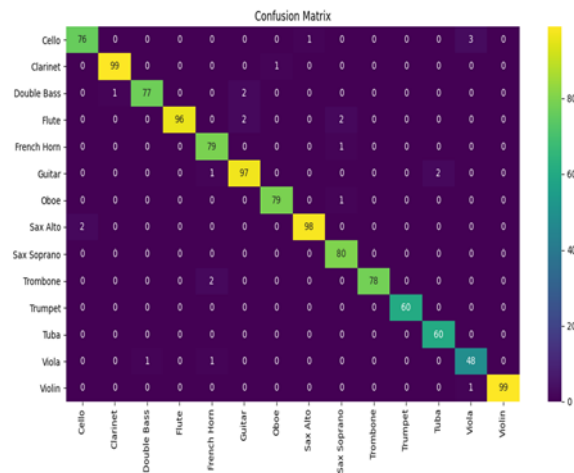


Fig. 10. Confusion matrix of Bi-LSTM.

Table 2. Performance of Bi-LSTM.

	Accuracy	Precision	Recall	F1 score
Cello	1.000	1.000	1.000	1.000
Clarinet	0.997	0.971	0.990	0.980
Double Bass	0.998	0.988	0.988	0.988
Flute	0.998	1.000	0.980	0.990
French Horn	0.996	0.952	0.988	0.969
Guitar	0.998	0.990	0.990	0.990
Oboe	0.999	1.000	0.988	0.994
Sax Alto	0.999	1.000	0.990	0.995
Sax Soprano	0.986	0.833	1.000	0.909
Trombone	1.000	1.000	1.000	1.000
Trumpet	0.996	0.966	0.950	0.958
Tuba	0.997	0.983	0.950	0.966
Viola	0.998	1.000	0.960	0.980
Violin	0.990	1.000	0.880	0.936
Overall	0.997	0.977	0.975	0.975

Using the same input as the Bi-LSTM classifier, the performance of 1D CNN is fairly consistent across all the instruments. As shown in Fig. 11 and Table 3, it obtained a perfect accuracy and an F1 score in trumpet, but the lowest F1 score of 0.941 in viola, due to a low precision of 0.923 caused by high false positive with 3 cases of cello and 1 case of violin wrongly predicted as viola. Note that all three are string instruments and it is possible that the features of some musical notes are similar.

**Fig. 11.** 1D CNN confusion matrix.

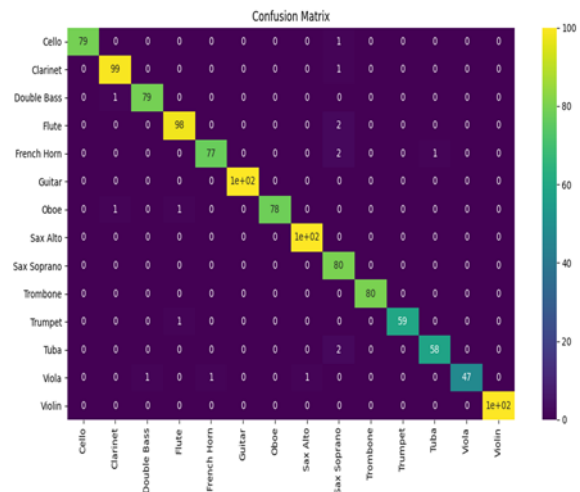
The results of 2D CNN are shown in Fig. 12 and Table 4. In contrary to Bi-LSTM, 2D CNN was observed to perform the best in violin with a perfect accuracy and an F1 score of 1. The same perfect score was also obtained in guitar and trombone. However, the model did poorly in sax soprano with a low precision of 0.909 and F1 score of 0.952, due to cases where cello, clarinet, flute, French horn and tuba were wrongly predicted as sax soprano.

Fig. 13 compares the F1 score of the 3 classifiers across the 14 instruments. While Bi-LSTM out-performed others in cello, flute, oboe and viola, it's extremely poor performance in sax soprano,

trumpet and violin resulted in the lowest F1 score among all 3 classifiers. It is worth to note that both Bi-LSTM and 2D CNN classifier did best in trombone and worst in sax soprano, while 1D CNN did best in trumpet and worst in viola.

Table 3. Performance of 1D CNN.

	Accuracy	Precision	Recall	F1 score
Cello	0.995	0.974	0.950	0.962
Clarinet	0.998	0.990	0.990	0.990
Double Bass	0.997	0.987	0.963	0.975
Flute	0.997	1.000	0.960	0.980
French Horn	0.996	0.952	0.988	0.969
Guitar	0.996	0.980	0.970	0.975
Oboe	0.997	0.963	0.988	0.975
Sax Alto	0.997	0.990	0.980	0.985
Sax Soprano	0.997	0.952	1.000	0.976
Trombone	0.998	1.000	0.975	0.987
Trumpet	1.000	1.000	1.000	1.000
Tuba	0.998	0.968	1.000	0.984
Viola	0.995	0.923	0.960	0.941
Violin	0.999	1.000	0.990	0.995
Overall	0.997	0.977	0.979	0.978

**Fig. 12.** 2D CNN confusion matrix.**Table 4.** Performance of 2D CNN.

	Accuracy	Precision	Recall	F1 score
Cello	0.999	1.000	0.988	0.994
Clarinet	0.997	0.980	0.990	0.985
Double Bass	0.998	0.988	0.988	0.988
Flute	0.998	0.980	0.980	0.980
French Horn	0.997	0.987	0.963	0.975
Guitar	1.000	1.000	1.000	1.000
Oboe	0.998	1.000	0.975	0.987
Sax Alto	0.999	0.990	1.000	0.995
Sax Soprano	0.993	0.909	1.000	0.952
Trombone	1.000	1.000	1.000	1.000
Trumpet	0.999	1.000	0.983	0.992
Tuba	0.997	0.983	0.967	0.975
Viola	0.997	1.000	0.940	0.969
Violin	1.000	1.000	1.000	1.000
Overall	0.998	0.987	0.984	0.985

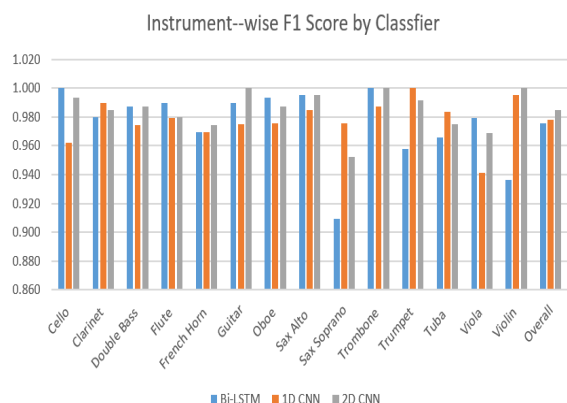


Fig. 13. F1 score of all instruments.

This research has demonstrated that 3 neural networks properly trained with the necessary spatiotemporal features are able to perform well with an accuracy and F1 score higher than 0.996 and 0.975 respectively in monophonic music. All 3 classifiers developed out-performed prior work [2, 7] that used CNN with Mel-spectrograms and [6, 15] that employed CNN with MFCCs.

5. Conclusions

Recognizing the correct musical instruments in audio tracks is important for the purpose of musical information retrieval. This paper investigated the combination of spatiotemporal features coupled with deep learning neural networks to classify musical instruments. Unlike the traditional approaches, the Mel-spectrograms of the musical signals were depicted as images.

However, musical data is complex, with the spectral characteristics overlapping temporal features. Moreover, music is a continuous signal too and it can be of different lengths with its pattern varying according to the sound tuning and filtering. Hence to cater for this particular consideration, the spatiotemporal features that were generated from the spectral and temporal characteristics of the musical notes were used in the musical instruments recognition model.

Three neural networks, namely Bi-LSTM recurrent neural network, 1-dimensional convolution network and 2-dimensional convolution neural network were examined using this approach to recognize 14 musical instruments through the monophonic musical tones. The log Mel-spectrogram of audio samples in Kaggle dataset were used for training and testing. All three models exhibited strong performance, with accuracy exceeding 0.996. Specifically, the 2D CNN achieved an F1 score of 0.985, while the 1D CNN and Bi-LSTM achieved scores of 0.977 and 0.976, respectively.

For future works, the proposed model are to be trained with polyphonic audio samples to investigate their ability to identify musical instruments on polyphonic music.

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A Systematic Review of Activity Monitoring and Measurement Systems in Elderly People with Dementia over the Last 5 years

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Abstract: This systematic literature review was conducted to explore systems for measuring and monitoring the activity routine of elderly people with dementia. It was identified and analyzed relevant studies evaluating the construction, effectiveness, and usability of these systems to improve the quality of life of this demographic group. This survey covered the exploration of multiple scientific databases, namely B-on, Google Scholar, PubMed, Science Direct and IEEE, covering the period from 2018 to 2023. The methodology of the different scientific studies, along with their results, as well as the characteristics of the study and the characteristics of the technologies were investigated. The final compilation consisted of 22 articles describing different measurement and monitoring tools. Gaps were identified in this final samples, as well as fields that still need to be addressed. Future research efforts should prioritize the development and refinement of robust, safe, and practical tools aimed at improving patients' quality of life and alleviating the responsibilities of their caregivers.

Keywords: Elderly, Dementia, Activities, Monitoring, Measurement, Systematic review.

1. Introduction

Dementia is a broad term including several illnesses that affects millions of individuals worldwide, particularly among the elderly population aged 65 years and older [1]. It is characterized by memory loss, cognitive impairment, behavioral changes, and functional limitations. Such symptoms can compromise and prevent the performance of activities of daily living [2].

In addition, according to the World Health Organization, in 2021 approximately 55 million people were living with dementia [3] and this number is likely to grow more and more with the increase of the elderly population. If the predictions come true, the number of people with dementia could reach the 139 million mark in the next 30 years [4, 5]. In this sense, it is important to find new solutions or strategies

that can help these older people to perform their daily activities without requiring continuous attention or help from their relatives and caregivers, or at least to improve their treatment with information provided on their daily activities.

On the other hand, it is important that the people responsible for the care of these patients can also have tools that help them to monitor these activities and facilitate this care. Therefore, recognizing and understanding the specific needs and challenges faced by the target group is crucial for developing adapted interventions and support systems. In this regard, this research sought to study the available systems to monitor the daily activities of elderly people with dementia, and the measured bio signals, as well as their effectiveness in improving the quality of life of these elderly people and their caregivers have been developed.

Through this systematic analysis of existing literature, the review provided an overview of the current state of the art, identifying gaps and limitations of existing studies and highlighted areas for further research and improvement. The results of this review serve as a basis for future evidence-based decision-making in healthcare settings, guiding the development and implementation of more effective and adapted measurement and monitoring systems.

This paper is organized in 5 sections. Section 2 describes the literature review methodology; Section 3 presents the results obtained; Section 4 shows the discussion and the strengths and limitations of the studies; and, finally, Section 5 presents the paper final considerations and remarks.

2. Methodology

2.1. Search Strategy

For the search strategy, it was applied the PICO (Patient/Population, Intervention, Comparison and Outcomes) framework [6-8]. For that, it was selected as demographic focus group elderly individuals affected by dementia. The intervention component concerns the measurement and monitoring systems, designed to supervise, and track the intrinsic aspects of the daily routines of the selected target population.

Concerning the comparison, it was defined all studies that perform comparative analysis, as well as different measurement and monitoring methodologies or that evaluated the effectiveness of available systems against pre-defined standards. Ultimately, regarding the outcome, it was performed a critical analysis focused on the identification of the role of the available devices to improve the quality of life, daily functioning and well-being of older people affected by dementia.

2.2. Databases, Keywords, and Filters

With the aim of an exhaustive exploration of the literature, a selected set of keywords was used. Variations of terms including, but not limited to, "routine measurement", "monitoring systems", "assessment systems", "older people", "dementia", "activities" and "technologies" were included. Through strategic integration with Boolean operators (AND, OR), these keywords were inserted into the search queries. Different scientific databases were used in this data collection, namely B-On, PubMed, Google Scholar, ScienceDirect and IEEE.

A total of 281 articles relevant to the scope were initially identified and exported to the Zotero platform [9]. Following a reading of the titles and a review of the inclusion and exclusion criteria, 92 articles were selected for a reading of the abstracts and conclusions. Subsequently, after a thorough review of abstracts and conclusions, the articles were refined in accordance with the criteria outlined in the forthcoming sections.

2.3. Selection Criteria

Concerning the inclusion criteria, only studies between 2018-2023 were considered. One of the main inclusion criteria was the selection of articles that provided specialized research in the field of monitoring and measurement systems for daily activities. At the same time, studies that focused on treatment modalities without patient data acquisition were removed. Articles written in languages other than English and Portuguese language are part of this exclusion list. Systematic reviews, meta-analyses, editorials, journal articles, magazine articles and book chapters were also excluded. All duplicates between databases were also removed.

2.4. Quality Criteria

The selection process for the articles in this study was also based on a set of quality criteria, with the aim of guaranteeing the integrity and credibility of the research results. First, priority was given to studies with a representative sample of elderly people with dementia. However, it was realized that large samples became difficult in some studies, due to the lack of necessary authorization.

In addition, the quality criteria gave priority to studies that incorporated validated and reliable measurement systems. In addition, the evaluation process included studies that employed methodologies capable of minimizing potential bias, both in terms of selection and confounding factors. Strategies such as randomization and pairing were considered.

3. Results

After the research process and considering all the established criteria, a collection of 22 articles was selected for final analysis. These carefully selected articles will be presented in the following subsection, organized in Table 1.

3.1. Characteristics of the Selected Studies

This section presents a detailed overview of the selected articles. Table 1 contains vital information, including the authors, the titles of the articles, the main characteristics of the studies and the types of technology used. The articles were also identified in the table for future reference in the review.

Among the articles identified, a trend emerges in which three of them [19, 22, 27] mainly investigate the feasibility of using already available technologies, rather than the details of the systems themselves. Although these studies do not focus precisely on the architecture of each system, they do provide some information on the operational dynamics of such technologies and their potential acceptance by patients.

Table 1. Selected Articles.

Index	Authors	Year	Title	Type of Technology	Characteristics
A1	Shao et al. [10]	2018	A Fuzzy Spiking Neural Network for Behavior Estimation by Multiple Environmental Sensors	Daily life monitoring system with environment sensor network.	The survey used a Partner robot, a guardian's smartphone, and various environmental sensors. The Fuzzy spiking neural network was also used to find sensor information that best reflects human behavior. An experiment was made in a house of four.
A2	Su et al. [11]	2018	Activity Recognition System for Dementia in Smart Homes based on Wearable Sensor Data	Wearable sensors and ambient sensors.	Study proposes augmented reality (AR) system in smart homes. Integrates internal positioning, hand movements using Random Forest and Dirichlet Process Mixture Model. Uses tri-grams for feature extraction.
A3	Obaid et al. [12]	2018	Automatic Food-Intake Monitoring System for Persons Living with Alzheimer's-Vision-Based Embedded System	Real-time vision-based device using raspberry pi 3 Plus and a 7-inch display with USB webcam.	The system employs innovative image processing techniques for hand and face detection designed to monitor food intake. It uses skin color detection through the HSV model, ensuring accurate tracking of hand movements. Experimental testing demonstrated an 89% accuracy in real-time scenarios.
A4	Yao et al. [13]	2018	Compressive Representation for Device-Free Activity Recognition with Passive RFID Signal Strength	Radio Frequency Identification (RFID)-based Compressive Sensing System for Unobtrusive Activity Recognition.	Focus on RFID and RSSI technology for activity tracking, without wearable devices. Applies dictionary learning and canonical correlation analysis. Validated in real-world experiments.
A5	Chun-Fang et al. [14]	2018	Indoor Positioning for Dementia in Smart Homes Based on Wearable Device	Bluetooth indoor positioning with the usage of accelerometer sensor and a gyroscope sensor.	The study integrates Bluetooth, accelerometer and gyroscope into a smart bracelet for indoor positioning. A Random Forest classification model processes the Bluetooth data for accurate positioning. Online tests adjust the results dynamically, taking real-time data into account.
A6	Yang et al. [15]	2019	Assistive and Monitoring Multifunctional Smart Crutch for Elderly	Multifunctional smart crutch.	The study proposes a multifunctional smart crutch using an Internet of Things (IoT) platform which enables GPS location, fall detection using a gyroscope and heart rate monitoring with the MAX30102 (integrated pulse oximetry and heart rate monitoring module). An assistance light feature adjusts the brightness based on the intensity of the ambient light.
A7	Takahashi et al. [16]	2019	Battery-less Shoe-Type Wearable Location Sensor System for Monitoring People with Dementia	Indoor location shoe sensor with battery independence.	The study presents a battery-free shoe sensor that uses the movement of walking to obtain energy. It achieved a 94.3% success rate in estimating indoor locations, with a successful 130-day trial in a nursing home.
A8	Thorpe et al. [17]	2019	Development of a Sensor-Based Behavioral Monitoring Solution to Support Dementia Care	Wearable sensor technology.	Study carried out with 5 healthy people, using a smartwatch and a smartphone with google APIS. The research focused on obtaining location, step count and activity recognition data.
A9	Huang et al. [18]	2019	Development of Health Care System Based on Wearable Devices	Smart clothes, body tag, and healthy watch.	The study involves integrating IoT with wearable devices, such as smart clothes and watches and body tags. The devices collect physiological signals from users, which are transmitted to a service server via Bluetooth. Includes care notification that enables real-time monitoring.
A10	Maiden et al. [19]	2019	Evaluating the Use of Daily Care Notes Software for Older People with Dementia	Daily notes system via mobile devices and desktops.	The survey was carried out using the Yammer Software application, with 18 caregivers, 2 team leaders and 13 patients of a residential home, as well as other health professionals who also had access to the notes.
A11	Kolakowski & Blachucki [20]	2019	Monitoring Wandering Behavior of Persons Suffering from Dementia Using BLE Based Localization System	Bluetooth Low Energy (BLE) based positioning system.	The system employs an Extended Kalman Filter algorithm to calculate user positions based on signals received from anchors distributed in a monitored area. The experiments involved tracking four dementia patients for three days.
A12	Lousado & Antunes [21]	2019	PRO2S – System for the Protection and Monitoring of the Elderly and Mentally Ill in Outdoor	Application integrated with sensor system.	The study looks at a system called PRO2S that uses the Internet of Things and ubiquitous computing for real-time monitoring. It incorporates an accelerometer, temperature, humidity, and pulse sensors into a bracelet. It provides immediate alerts in the event of abnormal situations.

Table 1. Continued.

Index	Authors	Year	Title	Type of Technology	Characteristics
A13	Dolatabadi et al. [22]	2019	The Feasibility of a Vision-Based Sensor for Longitudinal Monitoring of Mobility in Older Adults with Dementia	Vision-based sensor for tracking.	Study with 18 institutionalized elderly people. The setup included a Microsoft Kinect, a laptop computer, a radio frequency identification reader and two circularly polarized UHF antennas. Walking sequences were recorded, analyzed, and gait parameters extracted.
A14	Mibu & Shinomiya [23]	2020	Activity Recognition and Anomaly Detection for the Elderly with Dementia by using Passive RFID Sensor Tags	Passive radio frequency identification sensor tags.	The study employs passive radio frequency identification tags on everyday objects like trash boxes for unobtrusive monitoring. The system aims for easy installation, requiring no active cooperation from the elderly, and alerts caregivers or family members of meaningful anomalies.
A15	Pratama et al. [24]	2020	Geofencing Technology in Monitoring of Geriatric Patients Suffering from Dementia and Alzheimer	Geofencing surveillance system.	Patient monitored by a GPS device. If the monitored area is exceeded, the distance between the elderly person and the nearest caregiver is calculated using the Haversine method.
A16	Favela et al. [25]	2020	Monitoring Behavioral Symptoms of Dementia using Activity Trackers	Personalized behavioral symptom monitoring with activity trackers.	9 elderly people and 8 caregivers participated in the study. Two smartwatch models were used to collect data on steps per minute, heartbeats per minute and minutes of sleep. The data sought to evaluate behavioral changes related to dementia in participants in Cognitive Stimulation Therapy using the Eva robot.
A17	Raad et al. [26]	2021	An RFID-Based Monitoring and Localization System for Dementia Patients	Sirit radio frequency identification robust reader.	The study is based on RFID to track and monitor the elderly in a smart environment. The system uses battery-free RFID wearable tags. The system enables real-time tracking, issuing alerts in the event of potentially dangerous wandering outside predefined zones.
A18	Pu et al. [27]	2021	Portable EEG monitoring for older adults with dementia and chronic pain – A feasibility study	Pain monitoring through a portable EEG device.	Use of a portable headband for EEG measurement. Sample of 5 elderly people in an institution. The device is connected to a smartphone or other device capable of receiving data. The device was placed on different days, monitoring the level of pain perceived by the subjects.
A19	Basuki et al. [28]	2022	Audio Based Action Recognition for Monitoring Elderly Dementia Patients	Audio capture and action recognition with deep learning.	Usage of two hardware devices (Raspberry Pi 4B and ReSpeaker sensor). Usage of a Convolutional Neural Network. Usage of MQTT protocol to transmit the data to the backend platform.
A20	Au-Yeung et al. [29]	2022	Monitoring Behaviors of Patients with Late-stage Dementia Using Passive Environmental Sensing Approaches: A Case Series	Unobtrusive activity-sensing technologies to track behavioral markers.	Platform gathered participant data, including sensors under mattresses, movement sensors and actigraphy devices; other participants used Emerald sensors. Data correlated with medication, assessed by caregivers and doctors.
A21	Megalingam et al. [30]	2022	Indoor Tracking of Dementia Patients without GPS	Real time location systems.	The technology studied is a real-time localization system based on wireless sensor networks and NodeMCU microcontrollers. It uses proximity sensors, actuators, and an alert node to locate and monitor patients.
A22	Garcia-Requejo et al. [31]	2022	Indoor-Outdoor Tracking and Activity Monitoring System for Dementia Patients	Infrared-based positioning system.	A wearable device that integrates a Global Navigation Satellite Systems (GNSS) module, an accelerometer, and an infrared-based indoor positioning system. It communicates via LoRaWAN. The system includes The Things Stack cloud platform and Grafana. The wearable is equipped with an environmental sensor. The Lorix-One 868 MHz serves as a LoRaWAN gateway.

Studies A2, A5, A8, A9, A11, A12, A16, A18, A20 and A22 used devices directly linked to patients, such as smart watches and tags. Study A9 introduces for the first-time smart clothing. Study A10 was unique in its use of a technology managed solely by caregivers. Additionally, the other studies (A1, A3, A4, A6, A7, A13, A14, A15, A17, A19, A21) implemented remote monitoring technologies, eliminating the necessity for the elderly to carry a device.

In terms of monitoring methodologies, the research landscape reveals different aspects. Study A19 is the only one to propose audio capture and subsequent recognition for activity assessment. Studies A5, A6, A7, A8, A11, A13, A15, A17, A21, and A22 converge on geolocation strategies adapted to elderly people with dementia. With similar objectives, A8 and A16 used pedometer technology to assess ambulatory activity. Expanding the research repertoire, A8

emerged as a singular effort to delineate activities through sensor-activated inference. Study A6, on the other hand, brings a unique and innovative idea within the research carried out, since it promotes a monitoring system with both geolocation and falling detection functionalities.

Instead of automated processes, A10 introduced an annotation system mediated by the caregiver, facilitated by a smartphone app. Both A8 and A20 focused on the acquisition of sleep patterns, while A16 studied into heart rate monitoring. A20 and A13 used motion sensors to obtain data, although A13's study attempted to monitor each patient's gait. It is interesting to note that the A18 study used a portable EEG device to identify pain levels, the only study to look at pain in dementia patients.

Study A1 also innovates by using a partner robot that interacts with the elderly, providing a companion for conversations, as well as sensors that not only detect anomalies and activities, but also recognize drownings in the bathroom. Differently, study A3 proposes a vision-based system that monitors patients' food intake.

Finally, there are a notable number of studies on the use of radio frequency identification for different functions. Studies A4 and A17 propose the identification of activities through tags, with A4 presenting a dictionary and canonical correlation to detect such activities and A17 proposing the construction of an Android application to track and alert on location and suspicious activities. Study A14 implements tags on different objects, such as garbage cans, to check for anomalies in garbage disposal and thus be able to infer that something is wrong. Article A13 also features the use of radio frequency identification to locate patients.

The following subsection takes an in-depth look at the conclusions and results of these studies.

3.2. Presentation of Results

The selected studies cover a diverse range of approaches already used in the state-of-the-art for the development of monitoring systems, providing an insight into the current landscape of research dedicated to supporting individuals with dementia. In this section, a detailed analysis of each selected article is provided.

The first proposed system [10] integrates information, network, and robot technology, creating an Information Structure Space (ISS) to collect, store, transform and provide information. The sensor network for monitoring is composed of a daily life monitoring system, a partner robot system, and a behavior visualization system. The article introduces a Fuzzy Spiking Neural Network (FSNN) as a method for estimating behavior. The experiment involved four individuals, and the results showed an accuracy of 94.03 % in estimating behavior. Finally, the authors identified relevant challenges, such as delays in sensor

data, and express future goals of optimizing the system, reducing costs, and considering external factors such as seasonality.

Article A2 presents an Augmented Reality (AR) system for monitoring elderly people with dementia in smart homes. The system integrates data from on-body sensors (e.g., smartwatches with Bluetooth) and environmental sensors to monitor indoor positions and hand movements. The authors used machine learning algorithms such as Random Forest for indoor positioning and Dynamic Bayesian Network with Dirichlet Process Mixture Model for activity recognition. Here, the main feature is the use of a non-parametric grouping approach to categorize hand movements and integrate position information to distinguish similar activities. The proposed system achieved an accuracy rate of 99.1 % in recognizing complex activities related to "taking a medicine" and "eating a meal".

The third article [12] presented a real-time vision-based system designed to monitor food intake. Using the microcomputer Raspberry Pi 3 and a 7-inch screen, the system employed image processing techniques to detect hands and faces. It also uses skin color detection, ensuring accurate tracking of hand movements. The proposed structure defines an approach for tracking food intake activities, as well as engaging patients through video instructions. Experimental tests showed 89 % accuracy in real-time scenarios, demonstrating the system's potential to provide timely and independent support. Although the system is functional, it raised considerations related to the ethical implications of using images.

The study A4 presented a device-free, unobtrusive human activity recognition system based on RFID transmission signals. The proposed approach, which used a sparse representation based on a dictionary, demonstrated good results in detecting and classifying 23 postures and actions with an average accuracy of > 96 %. As a conclusion of the study, the results demonstrated the potential of the proposed approach for real applications in monitoring and assisting the elderly in their daily activities.

In the study A5, the authors developed an indoor positioning system for elderly people with dementia using smart bracelets equipped with Bluetooth sensors, an accelerometer, and a gyroscope. Considering the limitations of GPS, the authors also thought about the inconvenience of carrying smartphones. By combining Bluetooth-based positioning with data from motion sensors, the proposed method improved accuracy. The use of a median filter effectively reduced noise in the Bluetooth signal caused by environmental factors and body movements. The system demonstrated successful indoor localization, taking advantage of a finite state machine to refine the position results. The results suggested a promising approach to accurately locating the elderly in smart homes.

The A6 study introduced a different idea of a multifunctional smart crutch designed for elderly location monitoring, heart rate monitoring, fall

detection and supportive lighting for dark environments. Connected to the Internet of Things (IoT) platform, specifically using the China Mobile ONE-NET platform, the smart crutch enables real-time data transmission and accessibility for family members.

The seventh study [16] presented a battery-free location sensor included in a shoe to monitor the movement of elderly people with dementia. To address the challenges posed by battery-dependent portable sensors, the proposed system takes advantage of energy harvesting, specifically from the natural movement of walking, to power the transmitter built into the shoe. The experiment demonstrated that location estimation was successful, achieving a high success rate of 94.3 % in a controlled laboratory environment. In addition, the system was implemented and monitored in a real nursing home, where it successfully tracked the movement of an elderly woman with dementia for more than 130 days. These promising results suggest that the sensor developed can offer a reliable and maintenance-free solution.

The A8 [17] study, although successful in tracking behavior at home and identifying patterns, aiding predictive models and personalized interventions for dementia care, still needs to return this data to the health system to prove the real effectiveness of each of them in improving the quality of life of individuals. Furthermore, the success of studies carried out on healthy people may still run into several problems if carried out on people who have all the difficulties that dementia can offer.

The study A9 presented an IoT-based system that uses portable devices, including smart clothing, a health watch and body tags. The devices collect physiological data, such as electrocardiography signals and changes in attitude, which are transmitted to a service server. The system includes a Bluetooth to Wi-Fi gateway for data transmission and a care notification system for proactive health management. The results of the field implementation in a long-term care facility showed successful monitoring of the health status of residents, both for those suffering from chronic diseases and dementia. The system effectively detected abnormal events, provides immediate emergency notifications, and offers personalized health insights and questionnaires.

The A10 study [19], although not giving details of the system adopted, shows the successful adoption of the software by care providers. Positive results include an increase in the volume of daily care notes, improved readability, greater accessibility, and better preparation for activities. Usability considerations are highlighted, with the versatility of the software being crucial to overcoming barriers. Furthermore, the alignment of policies and technologies remains a challenge. Finally, as this is a study that relies on manual data input, it still needs research and evaluation of the best ways to maintain the reliability of the information collected.

The A11 [20] study is directly concerned with wandering behavior in individuals with dementia, and

for this it uses a location system based on Bluetooth Low Energy. The system consisted of a tag worn by the user, an infrastructure that includes a set of anchors distributed in the monitored area and a system controller. The system also employed an Extended Kalman Filter algorithm to calculate the users' positions based on the signals received from the anchors. The experiments, carried out in a long-term care center, involved monitoring four dementia patients for three days. The Bluetooth system demonstrated moderate accuracy in locating users, successfully detecting, and diagnosing some wandering incidents. However, monitoring is not yet automatic, preventing a more immediate response.

The study A12 presented a model called PRO2S (Protection and Security System). Taking advantage of the IoT and portable sensors, the system incorporates devices such as accelerometers, GPS, temperature, humidity, and pulse sensors, all integrated into a discreet wristband for the user's comfort. The system allows for real-time monitoring, guaranteeing the safety of users within predefined zones. Functional and non-functional requirements are discussed, as well as the systems architecture. The interface allows administrators to monitor users' outdoor activities, triggering alerts for anomalous situations. Future work includes refining the system based on the proof of concept presented, addressing energy sources, and customizing the technology for individual users.

The A13 study [22] demonstrated the feasibility of using the vision-based tool to longitudinally monitor gait in people with dementia. The tool successfully collected and analyzed gait data, providing information on walking patterns and gait measurements. This approach offers potential to improve falls risk assessment in long-term care by detecting changes in mobility patterns that may precede health events. Although portable sensors have limitations, vision-based systems such as AMBIENT are promising. Opportunities for improvement presented include refining participant identification methods, improving sensor placement and automating data processing.

Study number fourteen [23] proposed a non-intrusive monitoring system for elderly people living alone, using passive RFID sensor tags on everyday objects. The system aimed to detect anomalies in daily activities, such as leaving garbage or neglecting meals. Experiments focusing on garbage can monitoring revealed that changes in Received Signal Strength Indication (RSSI) values were correlated with the amount of garbage, enabling the detection of unattended garbage. In addition, temperature measurements on tableware indicated the potential to detect neglected meals. The results highlight the feasibility and effectiveness of the proposed RFID-based monitoring system.

The study A15 [24] used the Haversine distance calculation and a notification system to manage proximity between the care provider and the patient. Although generally successful, two trials failed due to

inaccuracies in the distance calculation. The dependence of the mobile device system on GPS signals led to lower accuracy. A further disadvantage emerged: the system does not monitor immobile patients. Future research was suggested that could include alerts of dangerous areas and notifications of patient immobility, as well as improving the effectiveness of GPS.

The A16 study [25] demonstrated the successful adoption of activity monitors by patients and caregivers for the assessment of dementia-related symptoms. Activity monitors provide valuable data on behavioral symptoms such as depression and apathy. Incorporating new sensors or raw data could improve the monitoring of other symptoms. Challenges include accuracy due to the limitations of the devices. Future research could explore advanced sensors and environmental data. Accelerometer raw data could estimate physical agitation and spatio-temporal gait parameters related to the risk of depression and dementia. The raw data would also allow for better monitoring of mobility and sedentary activity. The article also suggests incorporating microphones to assess socialization and including waterproof devices that are easier to use.

The study A17 presented a framework that uses low-cost, battery-free RFID wearable tags for the intelligent tracking of multiple people in a smart home environment. The proposed system employed a proximity-based indoor localization technique, using RFID antennas strategically placed in the living environment. The experiment demonstrated accurate, real-time monitoring of the elderly, detecting wandering behavior and triggering alerts via an Android application. The systems success lies in its ability to track up to three elderly people simultaneously, offering a promising solution for increasing the safety and well-being of people living alone.

A18 study [27] suggested that changes in pain-related brain regions are associated with changes in spontaneous brain activity, which may indicate pain processing. Portable EEG devices, such as the one used in the study, could serve as a low-cost, non-invasive tool for assessing pain in people with dementia. However, the small sample size and technical limitations of the study warrant further research for robust clinical applications. The feasibility of obtaining EEG data from residents with dementia was demonstrated, opening the possibility of EEG being a biomarker of pain for those who are unable to communicate. Finally, the article indicates that larger studies are needed to validate these results and compare portable EEG with medical-grade EEG for pain assessment.

While limited in scope, the study A19 [28] achieved a noteworthy 98 % accuracy in the audio capture, forwarding data to discern basic activities. Ongoing enhancements are warranted, including broadening recognized activities, and minimizing sensor dimensions.

The twentieth article selected [29] is a case series demonstrating the potential of discrete activity detection technology for monitoring people with dementia in their natural living environments. The technology implemented offered continuous, privacy-preserving data with the appropriate clinical implications, including the identification of behavioral changes and medication effects. The study also identified the need for further research to validate behavioral markers, guarantee privacy and establish transparency.

The proposed system by the penultimate article [30] uses a network of NodeMCU devices placed at exit points and on the patient, facilitating real-time monitoring in confined spaces such as homes or care centers. This system mitigated the limitations associated with GPS in smaller areas. The test showed favorable results, with minimal delay observed in the locally configured network. The cost-effectiveness of the system, with an estimated manufacturing cost significantly lower than that of alternatives on the market, increases its potential for widespread adoption. Future work aims to refine the design of the system so that it can be used incorporating low power consumption features, user-friendly interfaces, and additional functionalities such as voice processing.

Finally, the focus of the latest study [31] is on a wearable device based on a commercial tablet, incorporated with a GNSS module for outdoor location, an accelerometer for step detection and a LoRaWAN communications module. In addition, an infrared detector for indoor positioning enables symbolic indoor location using an infrared beacon system. The use of the communications module guarantees low power consumption and wide coverage in areas with limited access to the mobile network. Data on the patients position and steps are stored in a database, accessible via a web application. The system aims to help caregivers while promoting patient independence. Future efforts will involve integrating a fall detector, developing an Android application for alerts, and carrying out experimental tests with volunteers.

Following this exploration, in the next section (Discussion) it will be evaluated the strengths and weaknesses identified, aiming to provide a critical understanding of the state of the art of dementia monitoring systems and relevant challenges to be addressed in the future.

4. Discussion

Emerging technologies designed to measure and monitor activities hold great promise for improving care for older people with dementia, offering relevant improvements in standard care approaches and alleviating difficulties for caregivers.

According to our analysis, most of the available studies identified as challenging the recognition on anomalies in the activities of the elderly that could be

an indicator of dementia. Therefore, and to achieve a satisfactory performance in this task, most studies focus on a multiparameter evaluation strategy. Here, the fusion of various technologies as evidenced by the studies in this systematic review, reflects a broader movement towards innovative approaches. These encompass IoT, RFID, AR, and vision-based tools, each offering unique advantages on improving care for individuals with dementia.

It is important to note that the direct comparison between selected studies is not straightforward, due to the variables target group (i.e., different target group characteristics between studies), and a multitude of different goals, different scenarios and studied parameters (including different diseases).

Finally, while individual studies present laudable achievements, issues such as ethical implications, user acceptance and the practicality of implementation in various care settings emerge as recurring themes. For this reason, the main points of strength and weakness found in the studies will be presented below.

4.1. Strengths and Limitations of the Studies Included

At first, during the presentation of the results, it was possible to see that in the different technological scenarios described in the different studies, there is a common aspiration for real-time monitoring, evident in solutions such as AR systems [A2], smart crutches [15] and location sensors in shoes [16]. While the potential of these technologies is evident, a comprehensive discussion focuses on critical factors that influence their general adoption is still missing. Ethical considerations, long-term user acceptance and the practicality of implementation in various care settings emerge as critical points for the development of new technologies for detecting dementia.

The studies presenting vision-based tools for monitoring, exemplified by A3 and A13, demonstrated promising performances for improving falls risk assessment or problems with eating. However, a well-founded discussion should cover the limitations inherent in the methods of identifying participants, the need for automated data processing and the practicality of deploying such systems on a larger scale.

The exploration of IoT integration with portable sensors, exemplified in studies such as A9, A12 and A19, underlines the potential for efficient health monitoring. However, critical evaluation is essential to understand potential biases, scalability challenges and the adaptability of these systems in various care settings.

Considering the wearables (A2, A5, A8, A9, A11, A12, A16, A18, A20 and A22), despite being a practical, fast and reliable approach of obtaining patient information, it also presents several limitations, namely uncomfortable to wear, incorrect positioning can result in an incorrect measure and can be easily forgotten.

Lastly, it is also important to highlight that one of the studies under review focused in particular on the dyadic relationship between people with dementia and their caregivers [10], highlighting the key role of caregiver involvement [32]. This underlines the emphasis of research on the need to adequately prepare and integrate caregivers in the assessment and training of these technologies, helping them to obtain information, but also not helping that much on the burden of their work.

5. Final Remarks

The integration of technologies presents a promising avenue for improving the well-being of the geriatric population affected by dementia. Technological implementations show favorable results by providing auxiliary support to the elderly and their caregivers in the field of daily activities, while facilitating the assessment and optimization of medical interventions. Given the rapid pace of demographic ageing, the increasing prevalence of dementia and the expected treatment costs, monitoring technologies are set to play a key role in the daily lives of older people with dementia and their caregivers.

Empirical evidence underlines the satisfactory implications of monitoring paradigms, while at the same time highlighting the need for improvement. The use of pre-existing devices that interact seamlessly with common smartphones and smartwatches is clearly an economical and effective resource. However, the emergence of more sophisticated modalities, such as audio recognition systems, requires greater investment in research to discern their effectiveness. Given the lack of experimental research with substantial cohorts of participants and recognizing the profound implications for older people affected by dementia and their caregivers, further exploration in this field is clearly appropriate and it still a scientific challenge.

Therefore, based on our results, the way forward involves collaborative efforts between researchers, caregivers, and technology developers. Interdisciplinary dialogues, informed by both the successes and shortcomings highlighted in this analysis, could be critical in defining the next generation of technologies to monitor patients with dementia. By addressing the challenges identified and building on the strengths of existing systems, we can aspire to solutions that are not only technically efficient, but also ethically sound and life-changing for people affected by dementia.

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