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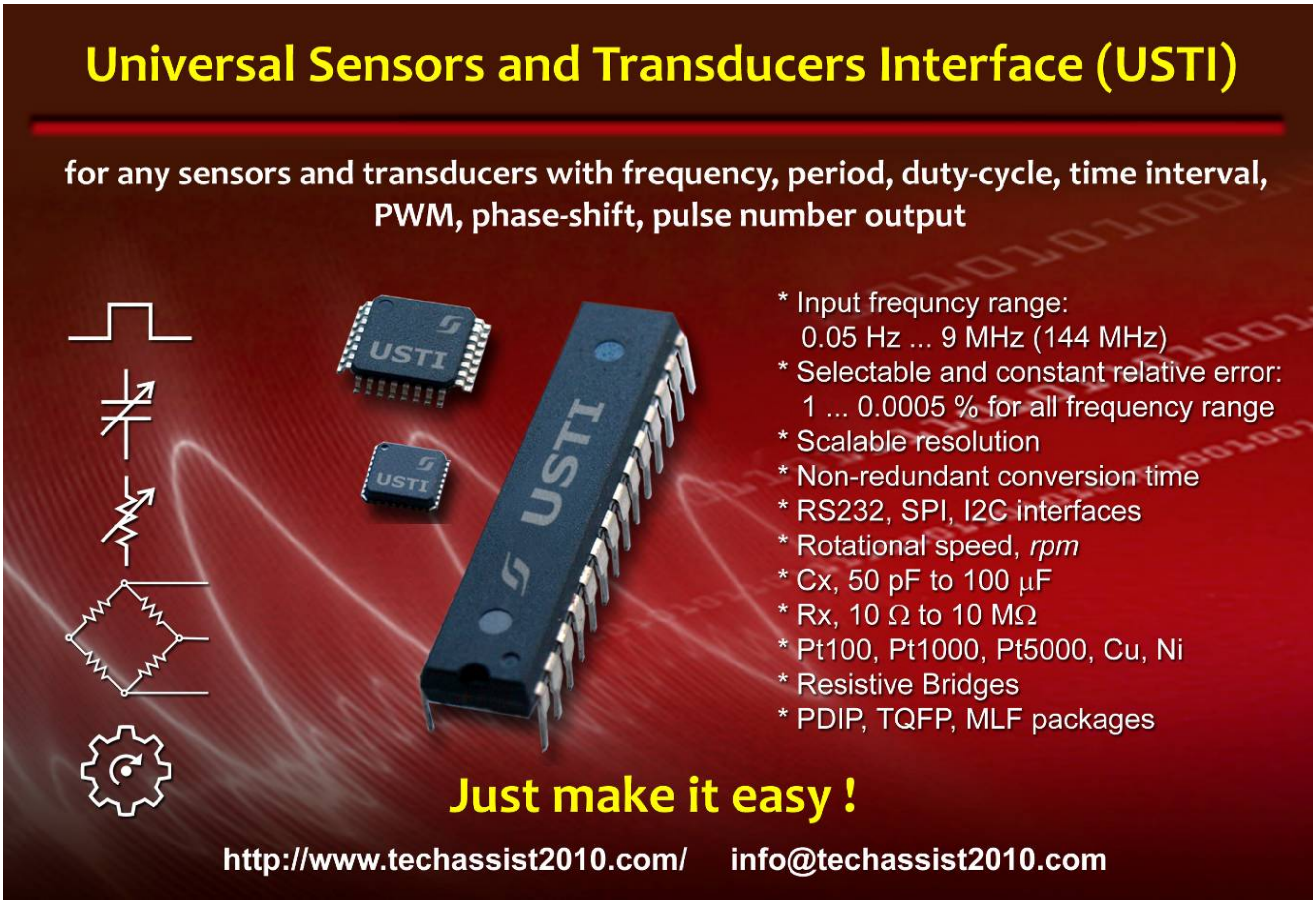
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Proposal for a Mini Wireless Force Platform for Human Gait Analysis

Giovani PIFFER and Alexandre BALBINOT
Instrumentation Laboratory (IEE)
Electrical Engineering Department (DELET)
Federal University of Rio Grande do Sul (UFRGS)
Av Osvaldo Aranha, 103, Porto Alegre, 90035-190, Brazil
Tel.: +550215133084440
E-mail: giovanipiffer@ibest.com.br, alexandre.balbinot@ufrgs.br

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Abstract: This paper aims to develop a mini wireless force platform placed in the shoe sole for analysis of human gait. The platform consists of a machined aluminum mechanical structure fixed into a sole, whose sensors are electrical resistance strain gages strategically cemented at the points of greatest deformation of the structure. The strain gages are configured as a ½ Wheatstone bridge connected to an amplifier for output signals and filtered by a signal conditioner. The signals are conditioned using a data acquisition board in conjunction with a graphical interface developed in LabVIEW. The static and dynamic behavior of the eight load cells was evaluated. Calibration at static pressures has shown that the eight load cells are linear within the usage range from 0 kgf to 45 kgf. The dynamic response has determined that the first vibration mode is around 1 kHz, indicating that the load cells have no resonance during the test. Three subjects carried out gait tests to examine the range of force platform use, and these tests demonstrated that the signals obtained are consistent with the classical references in this area. *Copyright © 2011 IFSA.*

Keywords: Load Cell, Strain-gage, Human Gait, Biomechanics, ZigBee.

1. Introduction

The improvement and development of new technologies have enabled a more accurate diagnosis and, consequently, more effective treatment and prevention of diseases. We can cite, for example, the development of new experimental systems for characterizing the human gait parameters [1-9].

The human gait is known to be one of the most complex forms of all human activities and its study has a multidisciplinary nature, involving many areas, e.g. [10-13], biomechanics [14-15]. Research on human gait may help determine some parameters that can be used as markers of health [16]. Disorders in human gait can affect different age groups and are related to various pathologies [17].

With the support of computational intelligence techniques, some studies have developed computer models to identify the gait cycle, with the main purpose of assisting in the diagnosis of disorders of the lower limbs, brain, and related to the aging process. Other studies have applied computer vision concepts for identifying people by examining their gait [16-30].

The development of force platforms is important in human gait analysis. Force platforms can be used in the study of human motion, to assess tremors related to specific psychopathological disorders, as well as in the study and development of new treatments [31-36].

The measurement of the foot-to-floor force interaction is admitted as a great value for locomotion analysis, both in itself and in connection with the measurement of kinematic data of body segments. Foot-to-floor interaction is commonly studied using force and pressure measurement systems. Force platforms are widely used both in posture and gait analysis [37-40].

Typically, the force platforms are medium to large rectangular plates fixed to the floor inside the laboratory or clinic. Fig. 1 represents simplistically a force platform with axes indicating the reaction forces acting on the body.

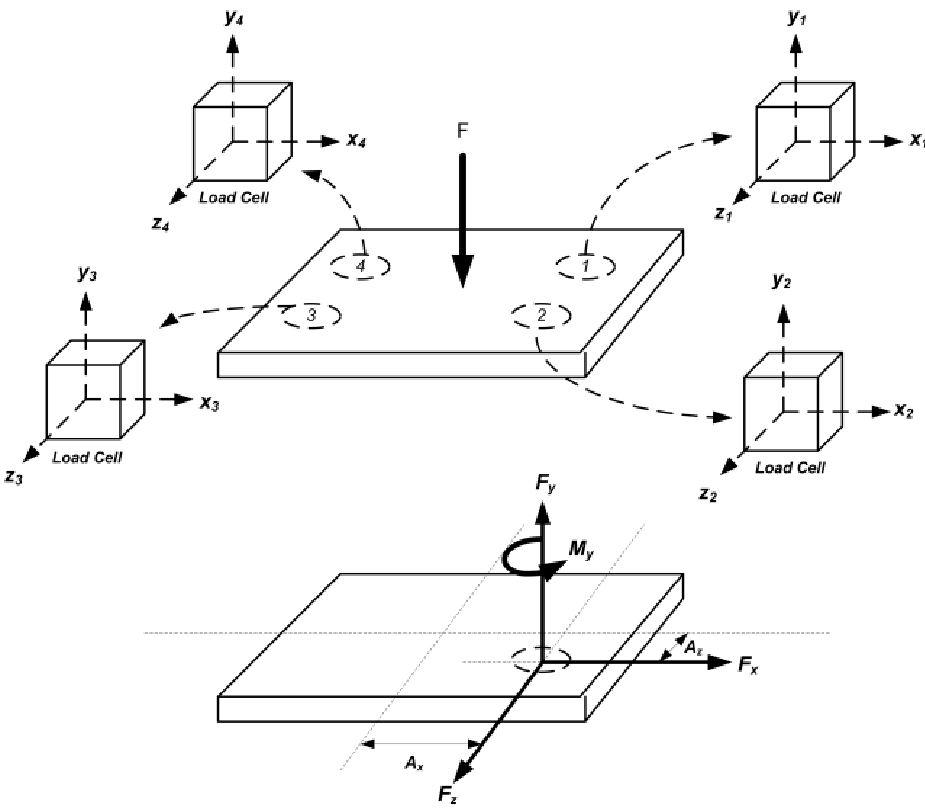


Fig. 1. A force platform sketch.

When an action force is applied to the platform, a reaction force acts on the body. Six variables are shown in this force platform, F_x, F_y and F_z, which represent the reaction forces along the coordinate axes x, y, and z; A_x and A_y are the coordinates the application point of force; and M_y, the moment around the y axis. If four load cells are positioned at four corners of this platform, the following reaction forces will be produced:

$$F_x = x_1 + x_2 + x_3 + x_4$$
$$F_y = y_1 + y_2 + y_3 + y_4$$
$$F_z = z_1 + z_2 + z_3 + z_4$$

The other variables can be obtained by:

$$A_x = \left[\left(y_1 + y_2 - y_3 - y_4 \right) \times b \right] / F_y$$
$$A_z = \left[\left(y_1 + y_4 - y_2 - y_3 \right) \times a \right] / F_y$$
$$M_y = \left(x_1 + x_2 - x_3 - x_4 \right) \times a + \left(z_1 + z_4 - z_2 - z_3 \right) \times b$$

in which the dimensions a and b represent the load cells distance from the force platform center in directions to z and x, respectively.

Interestingly, it has been found that in many experimental situations there is no cable connecting the transducer to conditioning system, mainly due to the involved distances, difficult access to measurement points, noise, amongst other factors. Telemetry systems by cellular phone, through Bluetooth, among others, are attached to the transducer, allowing wireless signal transmission. Currently, the integration of sensor technology with communication systems and digital electronics has allowed the development of tiny sensors with built conditioners (e.g. MEMS technology) and wireless, reducing costs in many experimental situations [1]. A measurement system based on wireless sensor consists basically on: sensor; signal conditioner (programmable amplifiers in general); multiplexing system; analogue (s) converter (s) for digital signal(s); microprocessor or microcontroller unit; supply system (depending on the backup cost); communication system, for example, a RF transceiver (Radio Frequency) and storage information system (e.g. a flash memory family). With respect to wireless sensors network, several topologies are found, including star, hybrid topologies (e.g. the standard known as ZigBee), and various standards, such as IEEE802.11, Bluetooth (IEEE802.15.1 and IEEE802.15.2), IEEE802.15.4 [41], IEEE1451.5, among others.

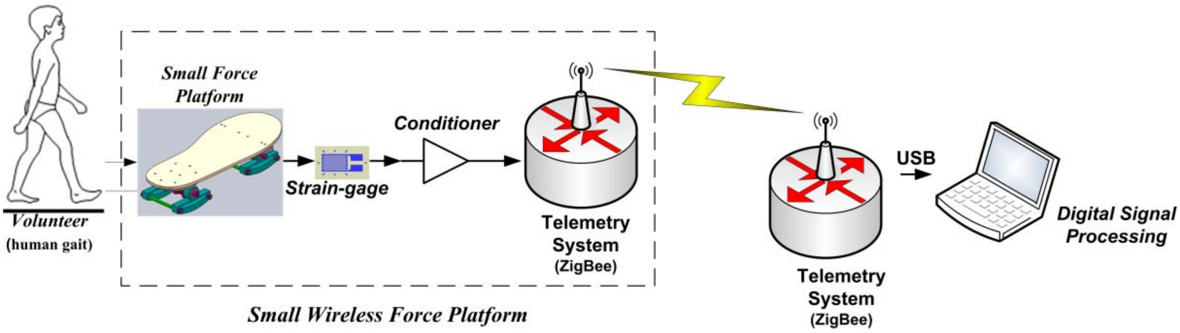
Aiming to contribute to the abovementioned field, this paper presents the study and development of a mini wireless force platform for human gait analysis, which can be fixed into a shoe sole, for obtaining more flexibility, that is, allowing testing in environments other than the laboratory or clinic. Several applications are possible with this system. We can monitor the clinical course in the recovery of injured people outside the hospital setting, assess the quality of shoe soles by measuring forces generated during walking, and, consequently, the ability to design and optimize damping in assembled structures on the shoe sole.

2. Experimental Section

2.1. Experimental System

Three healthy adult male volunteers participated in the present experiment. The mean age, height, and weight of the subjects were 27.2 years (range: 24 – 35), 1.77 m (1.77 – 1.79 m) and 76.3 kgf (67.0 – 86.0 kg), respectively. The subjects were sufficiently informed about the purpose of the experiment and the methods used prior to answering the questions, and gave their informed consent.

Fig. 2(a) shows the block diagram of the proposed experimental system. The first block represents the force platform consisting of a structure composed by several machined aluminum parts with four load cells for each footwear sole, sensors (strain gages in a Wheatstone bridge, on a ½ bridge configuration - this transducer has discrete steps from the stimulus until the desired response (Fig. 2(b)), sign conditioner and telemetry system (constituted by the ZigBee, battery and ADC).



(a)

(b)

Fig. 2. (a) System blocks diagram and (b) Transduction steps.

Mechanical stress $\left(\Delta G / G_N\right)$ causes relative deformations of $\left(\varepsilon = \Delta l / l_o\right)$ the elastic element (load cell) and relative variations in the initial resistance of the extensometers $\left(\Delta R / R_o\right)$ positioned on the elastic element surface. The relative variations in the strain gage resistances produce, for example, an imbalance in the output terminals of a Wheatstone bridge $\left(\Delta V_o / V_i\right)$, excited by a voltage reference or a current source. The strain gages on the elastic element surface cemented and connected to a Wheatstone bridge made it possible to obtain electrical signals proportional to the applied mechanical magnitude. Usually, a signal conditioner comprising one or more amplification stages and a low pass filter set at the frequency of the elastic element's oscillation that comprises the load cell to handle the Wheatstone bridge signal are used [42-44]. The signal conditioner, which is composed by an amplification step of two stages and of another step that consists of a low pass Buttherworth filter of 2nd order with cutoff frequency of 14Hz. The wireless transmission system is composed of a plate with the ZigBee transceiver and battery, responsible for acquiring and sending the output voltages of the eight load cells to another wireless reception system (plate equal to the one in the transmission system) through a microcomputer with USB interface, using the LabVIEW program to acquire and store the originated data from two force platforms, while running a gait test.

The design of the mechanical structure of a force platform should take into consideration the desired application and the specific problems in its manufacture and usage. An important aspect is the observation of the natural frequency of the parts that make up the mechanical set, which must go beyond the range of frequencies in the signal being measured. Based on the selected material specifications, such as hardness, elastic modulus and yield stress of the material, it is possible to determine this frequency. Accordingly, one normally attempts to produce structures with maximum stiffness combined with minimum weight.

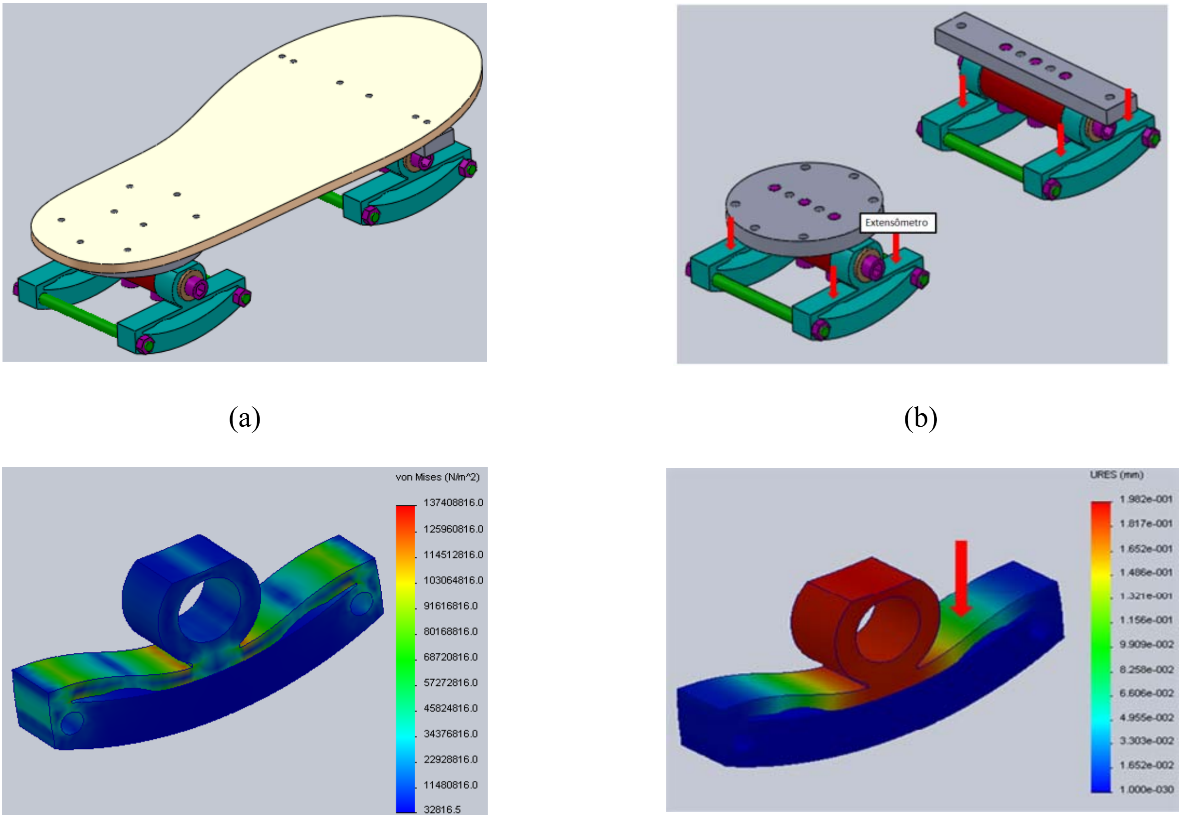
Initially, some studies were undertaken to determine the most appropriate mechanical arrangement for the force platform and for better suited geometry to the load cells as well as the type of material to be used. The main discussed issues related to the force platform project are: suitable mobility for the user during gait; subsets high rigidity that compose the force platform to prevent undesirable transverse deformations of the sensing elements; low cost and easy machining for both parts of the platform and for the load cells; easy cementation of the sensing elements in the load cells; a geometry allowing the load cell deformation without the risk of penetrating the plastic region during the human gait test.

Based on these questions, various geometries were assessed and then simulated in SolidWorks software for their corresponding mechanical behavior analysis. The following evaluation criteria were used in this simulation: decoupling of forces - the proposed load cells are uniaxial, i.e., measuring deformations in only one axis; stress values and minimum deformations and maximum values along the load cell; safety coefficient; limit runoff (in MPa) for the cementing region of the gages.

Aiming to reduce the weight, the 5052-F naval aluminum was considered, as it has good features for the machining, dimensional stability, and hardness between 40 and 50 HB (variable depending on thickness). It has a specific gravity of 2.80 g/cm^3, with one third less than the steel, providing a less wear and effort of the equipments built with it. Figs. 3(a) and 3(b) show the selected geometry for this force platform. The desired high rigidity is aimed to reduce as much as possible the bending and twisting of the subsets that compose the force platform, thus ensuring almost total transmission of the effort received by the surface of the support upper plates (during walking or running) to load cells placed immediately below. In this prototype, a slit-shaped "half moon" was included to concentrate the deformation in this region and create an optimized region for cementing the strain gages. This geometry was selected due to the machining moderate cost and also because of its good mobility during the gait on account of radius at the cell bottom. The gray plates convey the efforts of the bruising from the shoe sole to the load cells (blue parts). The conditioner plate was fixed between the spacer axles from each subset, above the steel axes (green) and below the aluminum axis (red).

Figs. 3(c) and 3(d) show the simulations for this load cell with a uniaxial loading in the vertical direction of 900 N (simulating the force platform usage by a person up to 90 kgf). The results indicated that the load cell works according to the elastic regime, since the maximum yield stress of the 5052-F naval aluminum is 98 MPa, indicating that this geometry is suitable for the proposed application. Analysis of the deformation diagram showed that the region indicated by the arrow has a deformation of 0.099 mm, which is within the range of the strain gage usage. The key elements that allowed this geometry selection were: high rigidity of the subsets that compose the force platform; appropriate mobility due to the radius of the bottom of the cells; flow voltages value below the maximum values for the cell material; moderate cost of production, since it does not require the side surfaces' machining and it has lower volume of removed material; low complexity machining of the load cell.

For the strain gage fixation (model: Kyowa, type: KFG-1-120-C1-11; gage factor: 2.11 ± 1.0 %; gage resistance: 119.8 Ω ± 0.2 Ω) inside the load cells, we followed all manufacturer's recommendations. Fig. 4 shows a block diagram with the design of the system's electronics (conditioning circuit). The REF02 voltage reference provides 10 V output power, and it is important to prevent undesirable fluctuations on the Wheatstone bridge output, in which the gages are mounted on ½ bridge configuration, depending on the available space for extensometers. The 10.00 V is reduced to -1.2 V using an inverting amplifier to prevent strain gage damage. The current in each arm of the Wheatstone bridge and, consequently, in each strain gage is limited to 5 mA. Following the inverting amplifier, there is a unity gain buffer that provides power for the remainder of the electronic circuitry. Following the Wheatstone bridge, there are two amplification stages with a total gain of 692. The output signal of the amplification stage is filtered by low pass Buttherworth filter of 2nd order with cutoff frequency of 14 Hz.



(a) (b)

(c) (d)

Fig. 3. (a) Design of the force platform, emphasizing the soles with holes for attachment, (b) mechanical set without the sole, highlighting the two load cells; the arrows indicate the location of the extensometers cementing, (c) numerical analysis by FEM of the yield strengths experienced by the cell and (d) FEM simulation from deformations in the cell - the arrow indicates the location of the extensometers cement.

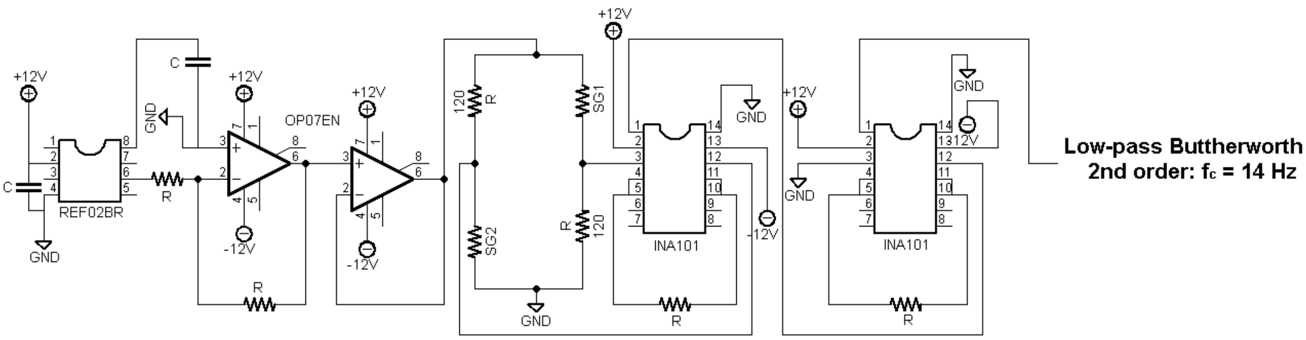


Fig. 4. A channel of the used conditioning circuit.

2.2. ZigBee Module

The wireless system proposed in this work consists of small devices, wireless transceivers (ZigBee - IEEE 802.15.4 protocol) and 4V batteries [48]. For communication, these modules generate a star network with a coordinator, who will capture the information on the modules and send them to a computer for calculation of the angles of the respective test. It will be possible then to record such data on a database and to obtain the repetition of the movement by virtual model of the human body in real-time).

The ZigBee transceiver is a wireless device that works on the IEEE 801.15.4 protocol [41], allowing the creation of a WPAN network (*Wireless Personal Area Network*). The main features of this device are low power consumption, support for various network settings, serial communication using UART (*Universal Asynchronous Receiver*), power management settings, eight digital inputs/outputs, four 10-bit Analog-to-Digital Converters, and two PWM (*Pulse-Width Modulation*) outputs, simple implementation, low cost interface, simplicity of the configuration, device redundancy, high node density per physical layer (PHY) and medium access control layer (MAC), and they allow the network to work with a great number of active devices – critical and interesting attribute for applications with sensors.

The IEEE 802.15.4 defines two kinds of devices: the Full Function Device (FFD) and the Reduced Function Device (RFD). The FFD was designed to coordinate the network and, thus, has access to all other devices. The RFD has only a star topology configuration, which is unable to operate as a network coordinator, and does not include all the protocol services. The FFD and RFD devices, defined by IEEE 802.15.4, can operate in three different ways at the ZigBee standard: as the ZigBee coordinator (ZC), ZigBee Router (ZR) or ZigBee End Device (ZED). The main functions of the ZC in the network (obligatorily an FFD device operating in active state) are parameter adjustments, information transmission, node management and information distribution between the nodes. The ZR (obligatorily an FFD) acts as an intermediary router, sending data to other devices, preserving the local network, keeping contact with its nearest neighbors, storing and transmitting data of interest of its associate devices (also known as children). The ZED can be of a RFD or FFD type and is not responsible for the routing network. They join the network through routers or coordinators, also known as parents. The NWK layer supports three topologies: star, cluster tree and mesh, according to Fig. 5. A star topology consists of a coordinating node and one or more final devices (FFD or RFD) that communicate with the ZC.

The interface of a ZigBee transceiver with the output of the force platform and a 4V battery determines the so-called "end device” that is part of the network ends. This device is positioned on the shoe sole, forming a star network, whose coordinator is in the center (configured ZigBee to manage the network, receive all the information from the end devices, and transmit the data to the computer via USB-serial interface). To operate the module, the end devices are configured to allow the use of the three internal analog-to-digital converters from ZigBee. The data acquired by ADC (Analog-to-Digital Converter) for each ZigBee (frequency of 1 kHz for each one of channels), is encapsulated in an API (Application Programming Interface) package, where a sample of each ADC is stored as set earlier in the transceiver. This package is sent to the coordinator by radio, which, in turn, sends the package to the computer via USB through a CON-USBBEE plate. New software has been developed on data receiving and processing to receive and filter the data and process the information. This process is repeated for each received package [48].

3. Results

It is possible to observe two subsets photo of the force platform with their respective signal conditioners in Fig. 6(a) picture of a partially loaded cell mounted on a given shoe (Fig. 6(b)).

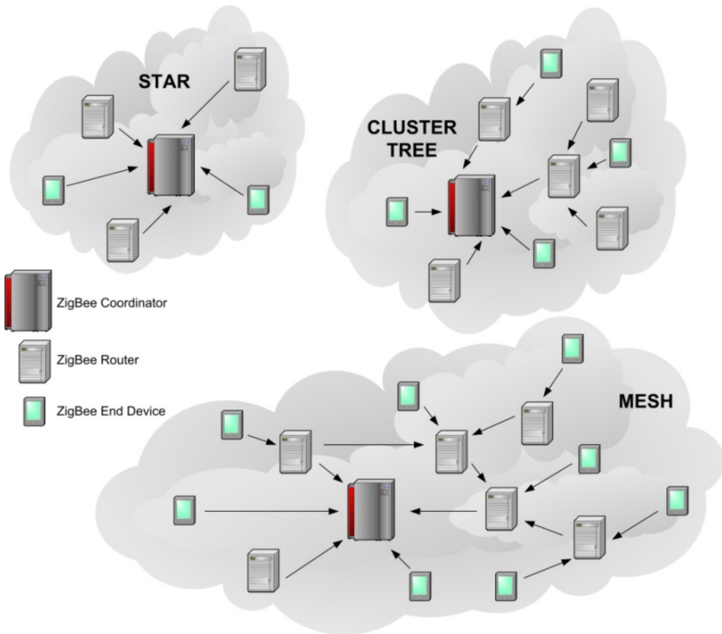
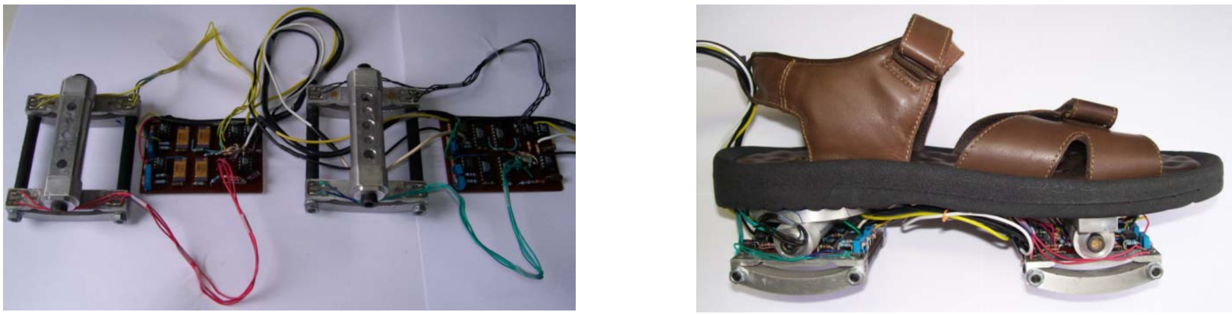


Fig. 5. ZigBee network topologies: star, cluster tree and mesh.

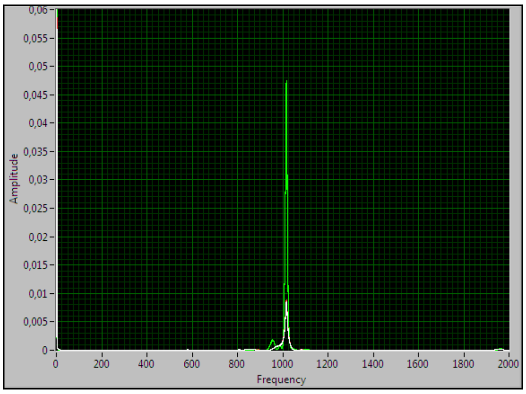


(a) (b)

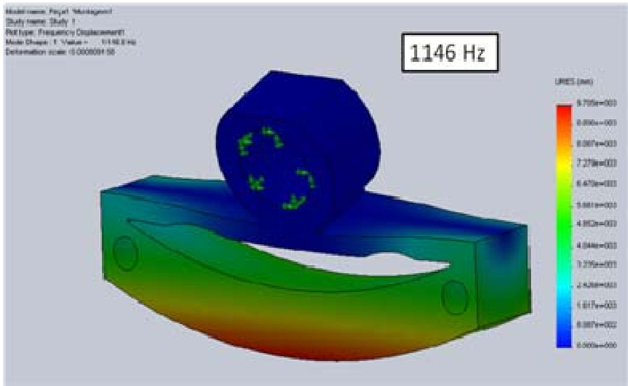
Fig. 6. (a) The subsets view of the force platform with its respective signal conditioners and (b) the subsets view of the force platform fixed to the base plates by M6 Allen screws.

The calibration process consists in obtaining the transfer functions that represent each of the eight load cells, allowing the establishment of correspondences between the applied forces values, as well as the assessment of parameters such as linearity and repeatability. For this procedure, a test machine was used with the purpose of applying known vertical efforts on each one of the developed load cells. The vertical test was carried out with a load of up to 45 kgf. Ten loads replicates of 0 to 45 kgf with a resolution of 1 kgf were performed for each load cell. We calculated the average among the voltage values for the same load, determining the power and transfer functions versus voltage for each one of the eight load cells. All eight load cells showed a linearity error of less than 1% for the desired range.

We applied a mechanical impulse on each one of the load cells to analyze their dynamic responses, i.e., their vibration modes. We used the conditioning system and NI SCXI-NI-100 card for the acquisition of data from National Instruments and a piezoelectric accelerometer model 4520 from Bruel & Kjaer. With the FFT of the signal from the Z axis accelerometer, it was possible to determine the resonant frequency of 1050 Hz for the first vibration mode (Fig. 7(a)). To compare this result, the vibration modes of the load cell were also simulated in SolidWorks. For the first vibration mode, this simulation result was 1146 Hz (Fig. 7(b)). Therefore, since the human gait frequency in these tests is around 5 Hz, it can be affirmed that the force platform will not come into resonance during its usage. Fig. 7(c) shows a picture of two platforms used by the study volunteers. Each volunteer was instructed to walk as naturally as possible. For gait tests, the power supply and data acquisition system were placed in a backpack carried by the users. The program developed in LabVIEW 9.0 allowed two hours of consecutive test for each volunteer with acquisition frequency of 1 kHz for each one of the channels.



(a)

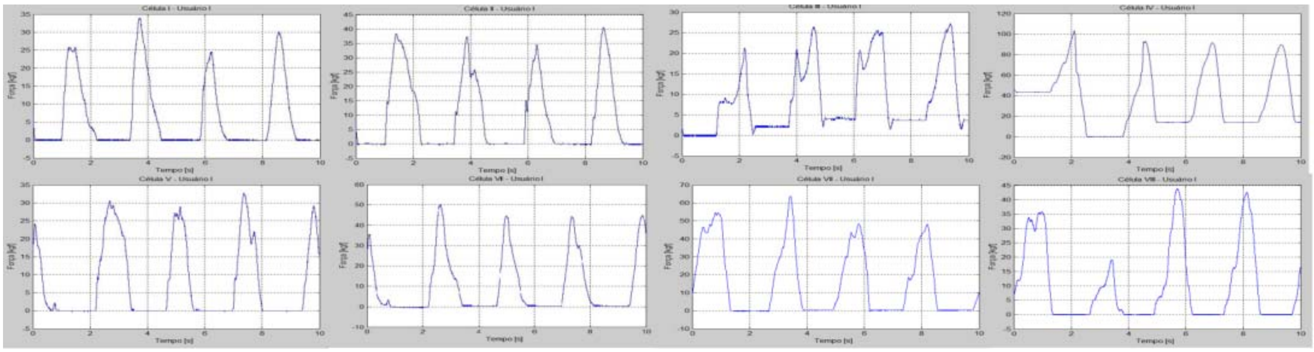


(b)

(c)

Fig. 7. (a) FFT of the accelerometer signal, (b) first vibration mode and (c) the platforms' photo.

Fig. 8(a) shows part (a ten second window) of one of the tests performed with one of the volunteers and Fig. 8(b), the zoom of the previous tests. Fig. 8(c) shows the support peaks, in which the first peak represents the initial cell VIII loading, followed by a reduction in loading and a maximum load, represented by the second support peak, which is the moment a considerable amount of the user's body mass on the load cell, obtains impulse to walk at a normal gait. We can observe the occurrence of two support peaks. According to several classic studies on human gait, the first peak represents the heel and the second peak represents the forefoot. It must be remembered that the force value reflects the changes in the center of a body mass movement.



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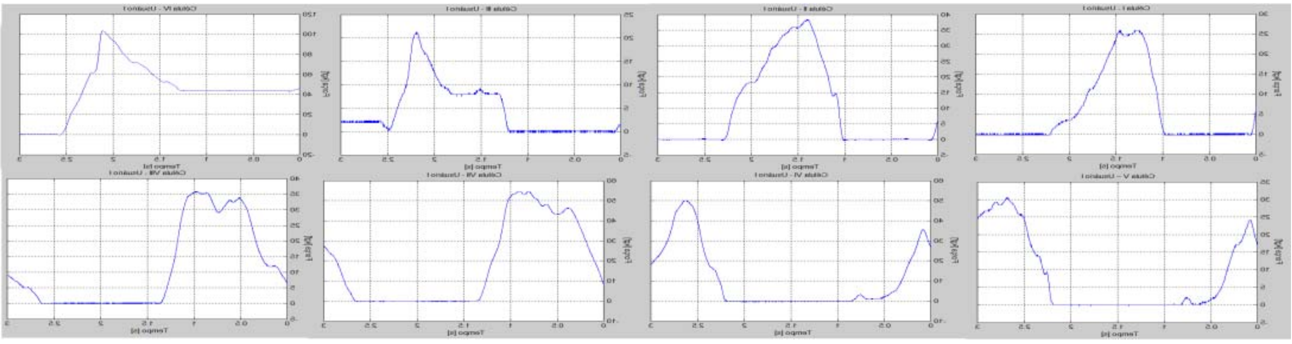

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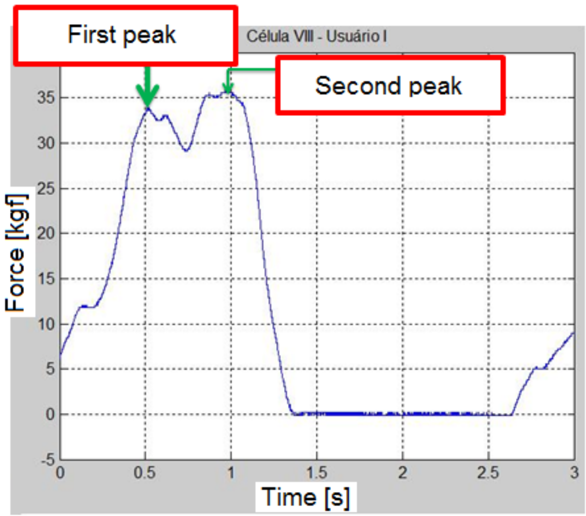

(c)

Fig. 8. (a) Window of 10s (from the eight load cells) from one of the gait test - voltage versus time; (b) zoom of the previous tests and (c) magnified graph of the cell number eight for the user I, highlighting the force peaks.

4. Discussions and Conclusions

For statistical validation, the methodology used was the "Design of Experiments with Several Factors: two-factor factorial experiments" [45-47]. The observations can be described approximately by the following linear model:

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \begin{cases} i = 1, 2, ..., a \\ j = 1, 2, ..., b \\ k = 1, 2, ..., n \end{cases}$$

in which Y_{ijk} (the variable response is the force on the vertical axis: F_y) is the random variable denoting the $(ij)^{th}$ trials for each volunteer (1 to 30), μ is the overall mean effect, τ_i is the *i* th level effect of *A* factor (three different volunteers), β_j is the *j* th level effect of *B* factor (two force platforms), $(\tau\beta)_{ij}$ is the interaction effect between *A* and *B*, and ε_{ijk} is a random error component having a normal distribution with mean zero and variance σ^2. This experimental design is a completely randomized design.

We decided to use $\alpha = 0.05$ (significance level). The sums of squares for the variance analysis (two-way variance analysis) are computed. The results of statistical analysis showed that the controllable factors *A*, *B*, and *AB* are significant, namely that the force applied by three volunteers during walking is different, the two force platforms responses are significant (i.e., the volunteers apply different forces on each leg, during the gait test), and the *AB* interaction is significant.

This work aimed at developing a small force platform for shoe soles. We have assessed some specific geometries, particularly regarding system mobility, frame rigidity and ease of platform's machining. The selected geometry in terms of these issues was built. The force platform has eight linear load cells within the usage range from 0 kgf to 45 kgf, with a resolution of 1kgf. The transfer functions of the eight load cells were determined with linearity error less than 1%.

We examined the load cell dynamic response to verify the vibration modes of this structure. The first vibration mode was determined experimentally by numerical simulation, and it is found in the range of 1 kHz, above the typical frequency range of human gait, which implies that the platform will never come into resonance when used under normal conditions.

Gait tests were performed with three volunteers, which allowed us to check and verify the correct operation of the designed force platform. Furthermore, it was possible to determine and verify the classical curve of force versus time for the vertical axis, similar to those found in the literature.

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Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

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Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

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