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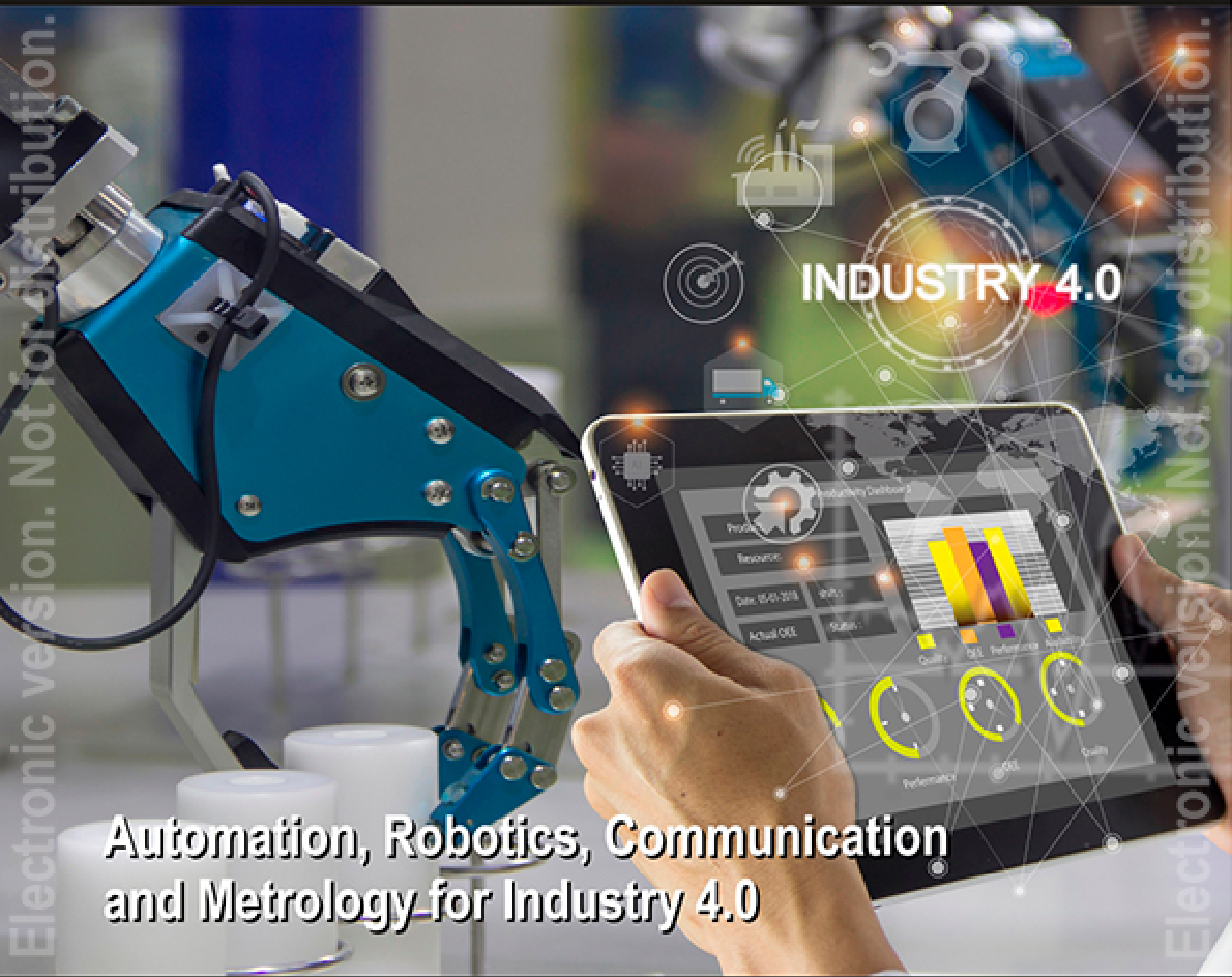

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Contents

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Research Articles

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Real-time Faults Prediction by Deep Learning with Multi-sensor Measurements over IoT Networks

[1, 2] G. Y. Luo, [3, *] Y. Q. Luo and [1] H. G. Gan

[1] School of Physics and Materials Science, Guangzhou University, Guangzhou 510006, China
[2] SHJ Medical Gas Specialists, Asheridge Road, Chesham HP5 2QA, UK
[3] Department of Mathematics, London School of Economics and Political Science, London WC2A 2AE, UK
E-mail: gaoyong.luo@yahoo.com

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Abstract: The advancements in sensing, data processing, and communication technology have enabled machine learning systems to make confident decisions and made it possible to optimise the operations and maintenance of the physical assets, manufacturing systems and processes of prediction and prevention. In many industrial applications, it is critical to use deep neural networks that make predictions both fast and accurate, and can be applied to coupled multiple-input multiple-output (MIMO) system of complex industrial processes. However, due to the difficulty in correctly interpreting the multi-sensor data and extracting the desired information, and the strong nonlinearity and its nearly instantaneous response to disturbances, it is still very challenging to achieve accurate faults prediction and optimised performance in such a complex MIMO system. In this paper, we propose to transform the raw multi-sensor data into the time-frequency domain by developing fast lifting wavelet transform with computational efficiency to obtain a big feature vector containing all the relevant features from all of the sensors, and giving more informative signatures for faults prediction. To raise the power and capabilities of machine learning, we propose a novel machine learning system designed by building IoT networks to remotely collect data, and developing deep wavelet neural networks (DWNN) with Gaussian (Mexican hat) wavelet derived as activation functions to improve nonlinear fitting and convergence speed, and to process the real-time data for faults prediction. Experimental results demonstrate that features extracted in time-frequency domain can reveal the presence of a fault, and its type and cause can be explained by the trained DWNN over the IoT communication networks, where the sensing capabilities and the computational power are provided by the designed controller, transmitter and cloud server to track everything that is relevant to operations, such that by deep learning with real-time data analytics we can have a knowledge base from which to predict faults, correct errors, optimize system performance and maximise efficiency.

Keywords: Real-time faults prediction, Machine learning, Deep wavelet neural network, Activation function, Data analytics in time-frequency domain, Wavelet analysis for feature extraction.

1. Introduction

The advancements in sensing, data processing, and communication technology have enabled the systems to interact with the environment and optimize processes via learning through interactions [1]. In particular, the increasing number of sensors and, in general, the available data sources provide the real-time monitoring and diagnostics of machines, systems, structures and processes, to be ever more detailed and intelligent [2]. This increases the potential for generating added value along the entire value chain by massive collection, evaluation and analytics on sensor data, and results in that the systems and architectures for data processing are becoming more and more complex, as the number of sensors is constantly increasing. Therefore, correct handling and interpretation of the data have become very important for real added value to be generated from the sensor signals. Depending on the application, it may be difficult to interpret the discrete sensor data correctly and extract the desired information. In addition, the dependencies between multiple sensors need to be explored and correlations to be established. For complex tasks, simple threshold values and manually determined logic are no longer sufficient or do not allow for automated adaptation to changing environmental conditions. In Industry 4.0 applications, with the advances in artificial intelligence (AI) and machine learning (ML), real-time data from various sensors and intelligent systems over the internet of things (IoT) networks can now be remotely collected and processed to monitor machine conditions, detect faults, predict and optimise system performance, which offer ways to optimise the operations and maintenance of the physical assets, manufacturing systems and processes of prediction and prevention, by enabling the technological innovation that the industry needs [2]. For example, engine and equipment failures are often associated with the internal or environmental variables exhibiting unexpected behaviors. Continuous monitoring of such variables, predicting failures or degradation and taking actions can prevent such events and provide predictive maintenance planning and scheduling. Equipped with multiple sensors over the IoT networks, and enabled by deep learning to detect relevant status information of the actuators and to monitor the health status of specific components [3], this new data-driven model is improving and dramatically changing the way how system/machine/engine/component failures can be predicted before they happen and that the downtime of industrial machines, engines can be prevented or reduced, extending from detection of anomalies to complex fault diagnostics and immediate initiation of fault elimination, thus leading to increased productivity. The resulting cost savings and competitive advantages are essential as the evolution and convergence of many new technologies - mechatronic systems, controllers, edge and cloud computing, big data, machine learning and the IoT, are being adopted and providing the basis for increasing the self-awareness of the machine, allowing it to optimise its own performance for the given duty cycles, diagnose and compensate for non-catastrophic faults, and coordinate operations with other machines with minimal input from the operator. From the perspective of production and service management, establishing the intelligent and communicative systems can enable the processes to deal with the data flow from intelligent and distributed system interaction and to promote autonomous interoperability, agility, flexibility, decision-making, and efficiency [4].

For real-time decision-making to give an early warning for catastrophic system damage, the voluminous sensor data generated in the IoT network needs data analysis. While diagnosis involves identifying the cause of an existing problem, prognosis can predict the occurrence of a problem and its cause. In recent times, data-driven prognosis methods have been proven to be very effective due to the availability of better data acquisition methods with multiple sensors, IoT and ML techniques. However, the characteristics of sensor data are complex, involving high velocities, huge volumes, dynamic values and types, real-time updating, critical data aging, and interdependency between different data sources [5]. Furthermore, the sensor data pollute while perpetuating numerous obstacles until producing the required data analysis and real-time decision-making. These make it difficult to extract relevant features directly from raw data in order to interpret and produce a representable form that is deliverable [6], and a reaction towards the external trigger. We propose to transform the raw data into the time-frequency domain by developing fast lifting wavelet transform with computational efficiency to obtain a big feature vector containing all the relevant features from all of the sensors, and giving more informative signatures for faults prediction and detection.

Through continuously acquiring sensor data to perform specific tasks, machine learning systems can carry out complex processes by learning from data with features extraction, rather than following the pre-programmed rules, allowing a more compelling and robust control architecture with optimised performance to be built on [7]. Automatic learning also vastly improves product quality by faults detection and condition monitoring that can introduce predictive maintenance systems into production processes, replacing visual inspections that can execute quality controls more accurately and efficiently. Indeed, deep learning is regarded as a foundational technology for complex applications such as faults prediction and predictive maintenance, and can be applied to coupled multiple-input multiple-output (MIMO) system of complex industrial processes. However, due to the strong nonlinearity and its nearly instantaneous response to disturbances, faults prediction with optimised performance in such a complex MIMO system is difficult to achieve [8]. It is required to build up appropriate research environments, and obtain datasets that can be used to explore and raise the power and capabilities of machine learning, where commonly used deep neural networks require improvements in nonlinear fitting and convergence speed. In this paper, we propose a novel machine learning system designed by building IoT network to remotely collect data, and developing deep wavelet neural networks using nonlinear Gaussian (Mexican hat) wavelet with sparsity as activation functions, to process the real-time data with features extraction in the time-frequency domain for faults prediction and detection to reduce downtime and increase productivity.

2. Machine Learning System

Real-time machine learning system is designed as shown in Fig. 1, where by designing printed circuit boards (PCBs) as machine controllers, signal collectors and transmitters, the IoT communication networks could be built for real-time remote monitoring, predicting failures or degradation, taking actions, and optimising system performance by machine learning, so that the predictive control and maintenance for highly efficient operation of industrial systems can be achieved [2]. The IoT allows objects to be sensed or controlled remotely across the built network, where fibre optic communication has been developed to increase data rates without electromagnetic or radio frequency interference (EMI/RFI), and to provide a cost effective way to transmit more sensor data with guaranteed safety. The wireless communication network based on self-developed protocol by an ultra-high frequency (UHF) radio frequency (RF) can achieve up to 2 km wireless link. With the IoT communication network built, real-time faults prediction and detection based on multi-sensor measurements can be performed by deep learning, so that we can have an eagle-eye view of every event while or before it's happening. It also enables real-time big data analytics to optimise decision making and performance, and to enhance productivity and e□ciency, creating an opportunity to apply real-time machine learning for advanced control, management and maintenance, by collecting data from all sources on the IoT networks, where qualitative and quantitative data analysis can build the next generation decision support system. This means current systems can be upgraded to suit the next generation needs of actioning changes in a process to optimise the efficient use of industrial systems, thus creating opportunities for industry 4.0 to be implemented with modernised products, systems and services, and also to improve precision, flexibility, and profitability. By real-time machine learning, the designed controller is able to predict and optimise control parameters to minimise energy consumption, while by real-time processing of measurement data provided by dedicated sensors installed in the machine, the system can enable autonomous decision making based on the online diagnosis of the correct machine with right condition, leading to increased machine reliability towards zero defects. Predictive maintenance based on condition monitoring by measuring such as vibration, acoustic, motor current etc., can then be planned and scheduled, such that we can have a knowledge base from which to correct errors and improve efficiency.

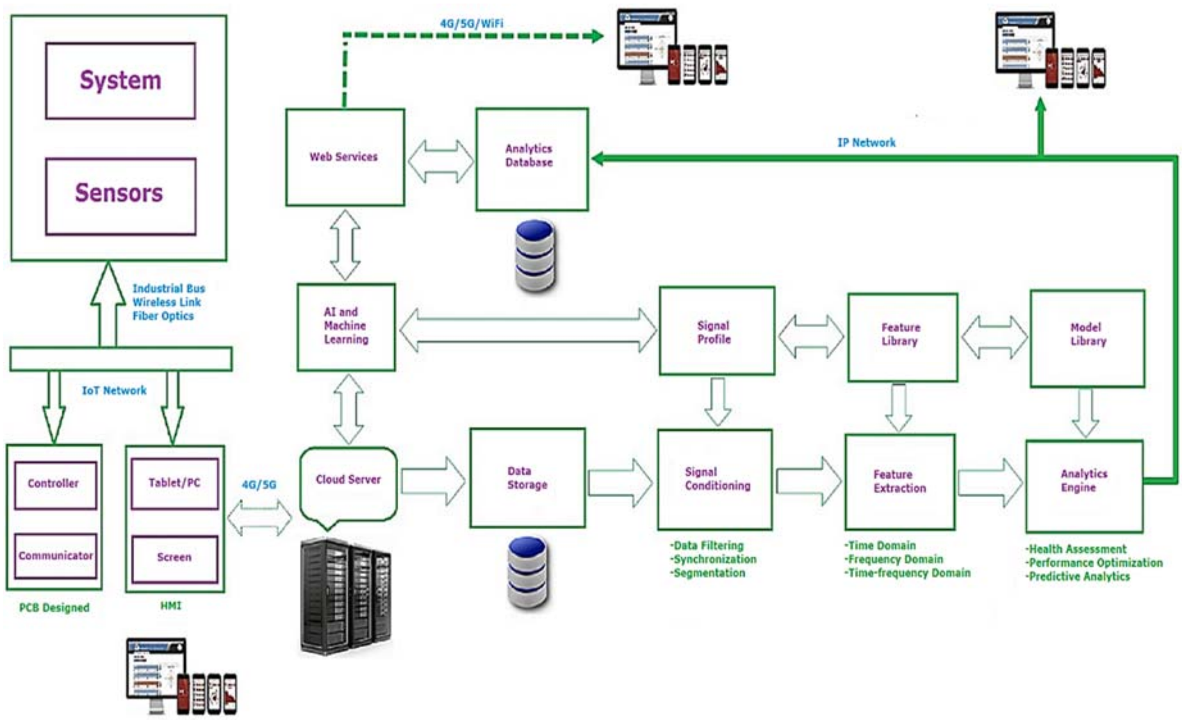

Fig. 1. Real-time machine learning system.

For MIMO systems of industrial processes, such as the multi-sensor signals as input to predict and detect time of faults as output, they can be modelled by the form of regression problem aimed at predicting:

$$Y = f(X) + \epsilon, \tag{1}$$

where $f(X)$ is an unknown function with inputs X and outputs Y, and ϵ is typically a white additive noise process represented by a random matrix. Prediction can be achieved by the nonlinearly mapping or fitting that models the observed past data, and we aim to minimise the mean squared error (MSE) between the actual inputs and predicted outputs at the training process.

For one input X_i and one output Y_m, we have

$$Y_m = f(X_i) + \epsilon_m$$

If $X_i = (x_t, x_{t-1}, x_{t-2}, \cdots, x_{t-j})$ represents the past data, and $Y_m = (y_{t+1}, y_{t+2}, \cdots, y_{t+k})$ denotes the prediction with k steps, the time-series forecasting would be:

$$(y_{t+1}, y_{t+2}, \cdots, y_{t+k}) = f(x_t, x_{t-1}, x_{t-2}, \cdots, x_{t-j}) + \epsilon_m, \quad (2)$$

where $i, j, k, m \in Z$ (Z is the set of all integers). The prediction is a complex nonlinear mapping where deep wavelet neural networks (DWNN) with nonlinear fitting can be used for faults prediction by monitoring multi-sensor signals with feature extracted in time-frequency domain.

3. Feature Extraction in Time-frequency Domain

For faults prediction, wavelet analysis that reveals time and frequency variant characteristics of faulty signal, can be used to zoom into a local region of interest in time-frequency domain, for fast and accurate monitoring and detection of any abnormal/fault operating condition. To extract features, a correlation coefficient between each signal and the healthy signal is assigned to the signal using wavelet analysis. With the property of time-frequency localisation, wavelets can detect the transient components related to large changes in signals [9]. For any given signal, wavelet transform can decompose this signal into many functions through translations (time index k) and dilations (frequency index j) of a single function called a mother wavelet, defined as $\Psi(t)$. The discrete wavelet transform (DWT) version is ($\Psi_{j,k}(t) = 2^{-j/2}\Psi(2^{-j}t - k)$) $j,k \in Z$, (Z represents the set of integers). A discrete wavelet transform maps the time domain signal of *y(t)* into a real-valued time-frequency domain and the signals are described by the wavelet coefficients as

$$y(t) = \sum_{j=1}^{J} \sum_{k=1}^{K} w_{j,k} \Psi_{j,k}(t) + \sum_{k=1}^{K} a_{J,k} \varphi_{J,k}(t), \quad (3)$$

where $w_{j,k}$ are wavelet (detail) coefficients and $a_{J,k}$ are the approximation coefficients which represent the smoothed part of the signal, $\varphi_{J,k}(t) = \varphi(2^{-J}t - k)$ is scaling function. The DWT is

$$w_{j,k} = \left|2^j\right|^{-\frac{1}{2}} \int_{-\infty}^{\infty} y(t)\overline{\Psi}\left(\frac{t - k2^j}{2^j}\right)dt, \qquad a_{J,k} = \int_{-\infty}^{\infty} y(t)\overline{\varphi}_{J,k}(t)dt \quad (4)$$

where $\overline{\Psi}, \overline{\varphi}$ denote the complex conjugate of mother wavelet Ψ, scaling function φ respectively.

The wavelet transform (WT) is a tool for carving up functions, operators, or data, into components of different frequency, allowing one to study each component separately. Wavelet analysis provides a mapping that has the ability to trade off time resolution for frequency resolution and vice versa. It is effectively a mathematical microscope, which allows the user to zoom on features of interest at different scales and locations. However, the need for improvement of wavelets comes from a shortcoming that is inherent because of its construction. Second generation wavelets were named when the concept of lifting was introduced [10], and opened a new direction to construct wavelets which are not necessarily translates and dilates of one fixed function. A construction using lifting is entirely spatial, and therefore ideally suited for building second generation wavelets when Fourier techniques are no longer available. Second generation wavelets are more general in the sense that all the classical wavelets can be generated by the lifting scheme. The lifting scheme makes optimal use of similarities between the high and low pass filters so as to achieve a faster implementation of WT. To give more flexibility to design wavelet filter with linear phase for fast implementation, we propose to use biorthogonal wavelet transform by lifting scheme [10].

Classical implementation of WT uses two band filter bank (FB) with recursion on its low pass (LP). Equivalent polyphase representation is depicted by polyphase matrix $\widetilde{P}(z)$, which is assembled from even and odd filter components. Output of the FB analysis part is then:

$$\begin{bmatrix} LP \\ HP \end{bmatrix} = \widetilde{P}(z)\begin{bmatrix} y_{even} \\ z^{-1}y_{odd} \end{bmatrix}, \quad (5)$$

where HP denotes high pass and y_{even} is the even part of the signal, and y_{odd} is the odd part.

$$\widetilde{P}(z) = \begin{bmatrix} \widetilde{h}_e(z) & \widetilde{h}_o(z) \\ \widetilde{g}_e(z) & \widetilde{g}_o(z) \end{bmatrix} \quad (6)$$

For any filter pair (h, g) with $\det[P(z)] = 1$, always exist factorization of $P(z)$ [11]:

$$P(z) = \begin{bmatrix} K & 0 \\ 0 & \frac{1}{K} \end{bmatrix} \prod_{i=m}^{1} \left\{ \begin{bmatrix} 1 & s_i(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ t_i(z) & 1 \end{bmatrix} \right\} \quad (7)$$

Eq. (7) allows ladder realization of $\widetilde{P}(z)$ by reversible lifting steps followed with normalization by factor K as shown in Fig. 2.

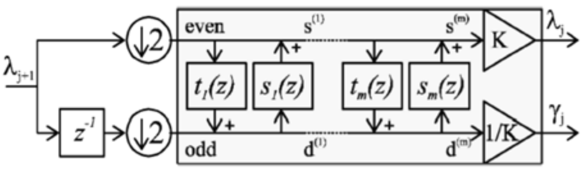

Fig. 2. Ladder structure of lifting steps.

Signal is partitioned into even and odd components that are then mutually predicted by t_i (to zero signal in HP part) and updated by s_i (to retain in LP part signal moments). After normalization, the algorithm is recursively applied to the LP part. Backward transforms simply undo all ladder steps from right to left using reversed operators. So by lifting wavelet transform, signals can be decomposed into a series of subband signals with the use of a multi-resolution analytical property, where features related to faults prediction and detection are extracted in time-frequency domain, and can be used to train and test the deep learning model.

4. Deep Wavelet Neural Networks

To better map the inputs to outputs with highly nonlinear relationships, we construct deep wavelet neural networks (DWNN) as shown in Fig. 3.

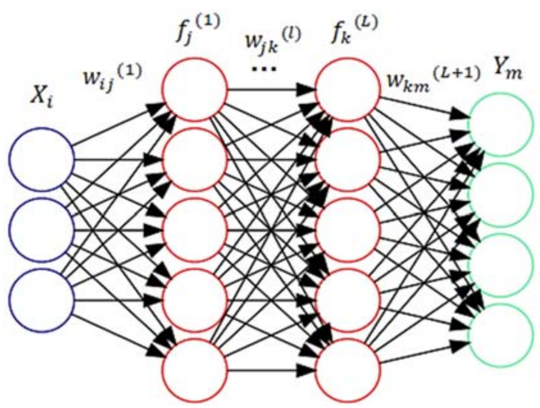

Fig. 3. A deep wavelet neural network (DWNN).

The prediction output Y_m can be expressed by deep prediction rule:

$$\begin{aligned} Y^{(1)} &= f^{(1)}\left(W^{(1)}X_i + B^{(1)}\right), \\ Y^{(2)} &= f^{(2)}\left(W^{(2)}Y^{(1)} + B^{(2)}\right), \\ &\vdots \\ Y^{(L)} &= f^{(L)}\left(W^{(L)}Y^{(L-1)} + B^{(L)}\right), \\ Y_m &= W^{(L+1)}Y^{(L)} + B^{(L+1)}, \end{aligned} \quad (8)$$

where f is a wavelet function that is used as activation function to construct the DWNN, W is the weight matrix and B denotes bias. Rewrite Eq. (2) by the analysis of variance (ANOVA) expansion [12]:

$$\begin{aligned} y(t) &= f\left(x_1(t), x_2(t), \cdots, x_n(t)\right) + e(t) \\ &= f_0 + \textstyle\sum_{i=1}^{n} f_i\left(x_i(t)\right) + \textstyle\sum_{1\le i<j\le n} f_{ij}\left(x_i(t), x_j(t)\right) \\ &+ \sum_{1\le i<j<k\le n} f_{ijk}\left(x_i(t), x_j(t), x_k(t)\right) + \cdots \\ &+ \sum_{1\le i_1<\cdots<i_m\le n} f_{i_1 i_2\cdots i_m}\left(x_{i_1}(t), x_{i_2}(t), \cdots, x_{i_m}(t)\right) \\ &+ \cdots + f_{12\cdots n}\left(x_1(t), x_2(t), \cdots, x_n(t)\right) + e(t), \end{aligned} \quad (9)$$

where $i_1, i_2, \cdots, i_m, m, n \in \mathrm{Z}$.

For any function $f \in L^2(\boldsymbol{R})$, the form of wavelet decomposition is

$$f(x) = \sum_j \sum_k c_{j,k}\psi_{j,k}(x) = \sum_{m=1}^{M} c_m \psi_m(x) \quad (10)$$

For an n-dimensional wavelet

$$\psi^{[n]} = \psi^{[n]}(x_1, x_2, \cdots, x_n) = \prod_{i=1}^{n} \psi(x_i)$$

If we choose Gaussian wavelet functions, we have

$$\psi^{[n]} = \psi^{[n]}(x_1, x_2, \cdots, x_n) = x_1 x_2 \cdots x_n e^{-\frac{\|x\|^2}{2}}, \quad (11)$$

where $\|x\|^2 = \sum_{i=1}^{n} x_i^2$. In this study, we use Mexican hat wavelet as activation functions. It is the negative normalised second derivative of a Gaussian function and has admissibility condition and a symmetric structure.

$$\psi_{mexh}(t) = \frac{2}{\sqrt{3}\pi^{\frac{1}{4}}}(1 - t^2)e^{-\frac{t^2}{2}} \quad (12)$$

Its derivative is also a Gaussian function:

$$\psi'_{mexh}(t) = \frac{2t}{\sqrt{3}\pi^{\frac{1}{4}}}(t^2 - 3)e^{-\frac{t^2}{2}}$$

Thus, the expansion component $f_{i_1 i_2\cdots i_m}(x_{i_1}(t), x_{i_2}(t), \cdots, x_{i_m}(t))$ can be expressed by DWNN model:

$$f_{i_1 i_2\cdots i_m}\left(x_{i_1}(t), x_{i_2}(t), \cdots, x_{i_m}(t)\right) = \textstyle\sum_{j=j_m}^{J_m} \sum_{k_1\in K_j} \cdots \displaystyle\sum_{k_m\in K_j} c_{j;k_1,\cdots,k_m}\psi^{[m]}_{j;k_1,\cdots,k_m}(x_{i_1}(t), x_{i_2}(t), \cdots, x_{i_m}(t)), \quad (13)$$

where $k_1, k_2, \cdots, k_m, j_m, J_m, K_j \in \mathrm{Z}$.

Compared with commonly used deep neural networks, using nonlinear Gaussian (Mexican hat) wavelet with sparsity as activation functions in the DWNN model can improve nonlinear fitting and convergence speed with adaptive learning rate, so that the power and capabilities of machine learning can be raised.

To predict faults from multi-sensor measurements, DWNN network is constructed. Fig. 4 gives an example of DWNN network to train 4 sensor signals as input, and faults prediction as output including predicting the time when system is operating at normal, or first warning, second warning, and fault detected when or before it is happening. After faults prediction and detection, the machine learning system will also be trained to learn and diagnose what cause the faults and what actions can be taken to prevent or reduce them if an early warning of faults is given by deep learning.

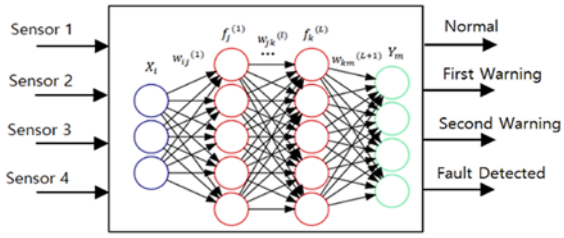

Fig. 4. Faults prediction by DWNN.

5. Experiments

To evaluate the proposed DWNN for faults prediction with multi-sensor measurements, unmanned medical air plant to provide oxygen was set up as shown in Fig. 5. It consists of four compressors and one oxygen generator (OG) to compress and purify oxygen for hospital users.

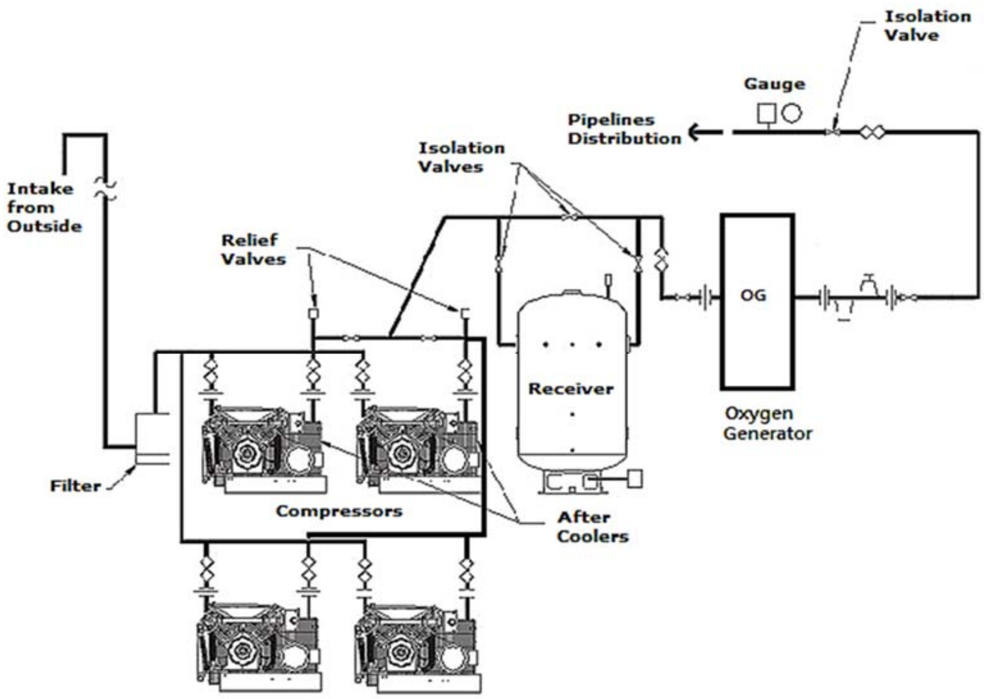

Fig. 5. Unmanned medical air plant for oxygen supply.

Based on the choice of fixed speed compressor, and with remote monitoring of multi-sensor signals over the built IoT networks and real-time machine learning for faults prediction, the measurement signals of mains current (to measure status of compressor operating), flow rate (at pipeline output), oxygen line pressure (at pipeline output), oxygen purity (to measure the quality of oxygen) are remotely collected over IoT networks and processed at cloud server, where deep learning by DWNN is performed. The measurement data analysis shown in Fig. 6 is from data of 4 sensors recorded in about one week's time, during which faults were detected because oxygen purity was lower than a preset level that is not acceptable for medical use. Fig. 7 shows the same signals in frequency domain, indicating strong fundamental (compressor loading period) and harmonic frequencies, and details of multi-sensor measurement signals in time domain are shown in Fig. 8, where the system was operating at normal conditions with no fault being detected. It can be seen that under normal conditions, compressors are operating at a loading and off-loading cycle, and that makes the sensor values of flow rate and oxygen line pressure vary at the same cycle.

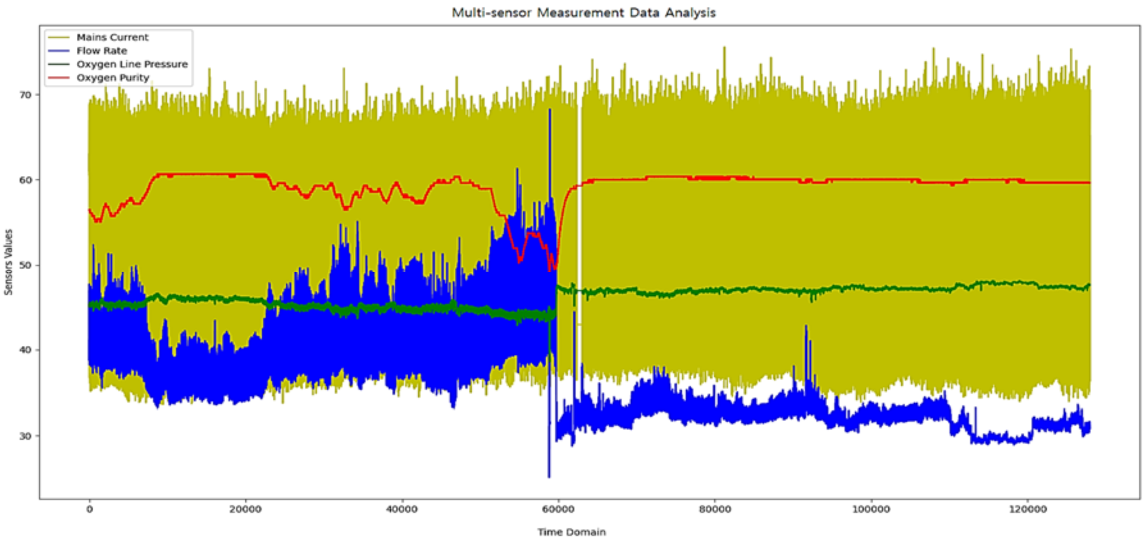

Fig. 6. Multi-sensor measurement signals in time domain.

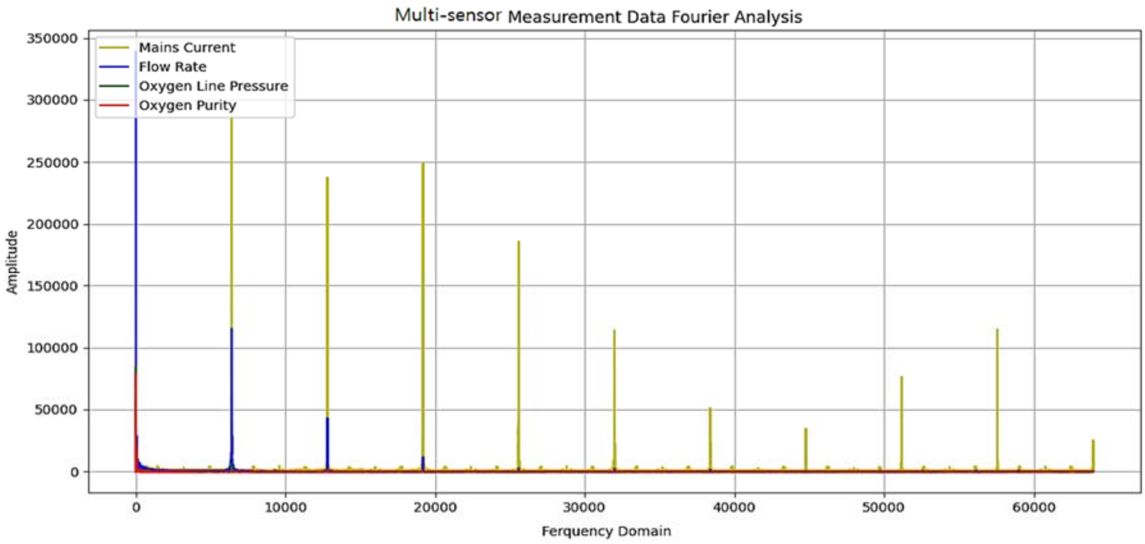

Fig. 7. Multi-sensor measurement signals in frequency domain.

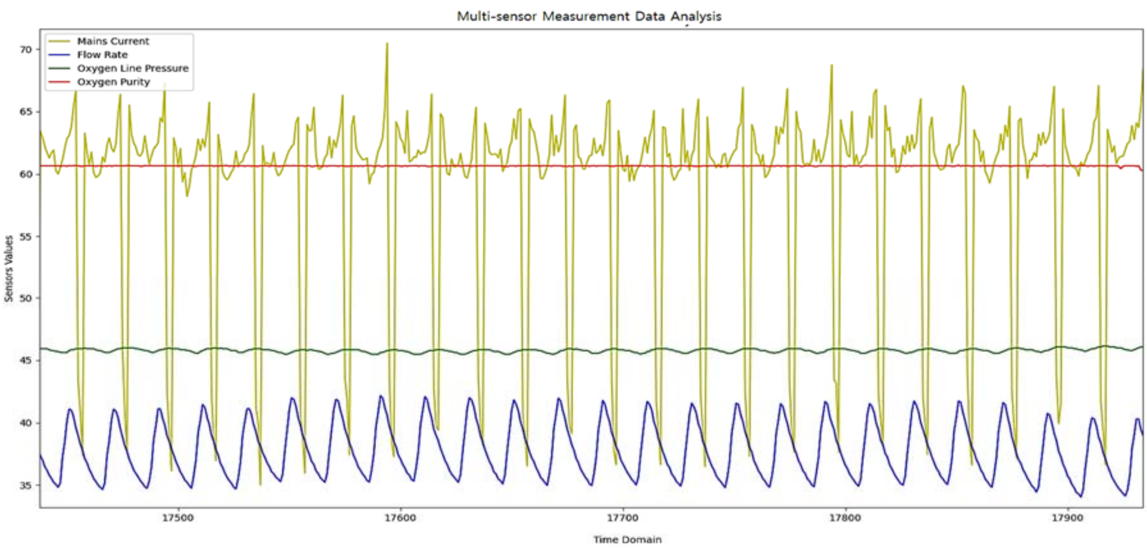

Fig. 8. Details of multi-sensor measurement signals in time domain.

The collected data analysis in time domain (as time series: a sequence of data indexed by successive time points) can only provide limited information for faults prediction, giving no warning before they happen. Therefore there is a need to represent the data information contained within such time series in a more detailed or meaningful form, where features can be extracted to reveal the change of operation conditions. As wavelets are able to give a time-frequency representation of a signal, we developed fast lifting wavelet transform that can create a representation of the signal in both the time and frequency domain, allowing efficient access of localised information about the signals. Fig. 9 shows the same signals as in Fig. 6 represented in time-frequency domain, where each signal is decomposed by wavelets into low and high frequency parts. Thus the features extracted in the time-frequency representations can be used to feed the DWNN network for predicting faults. The training was performed offline to obtain the optimal network parameters. Tests can be performed online to predict the timing of system conditions in four stages: normal, first warning, second warning, and fault detected if there is any. Fig. 10 gives a detailed example of how they are detected and thus can be used for deep learning to predict before they appear.

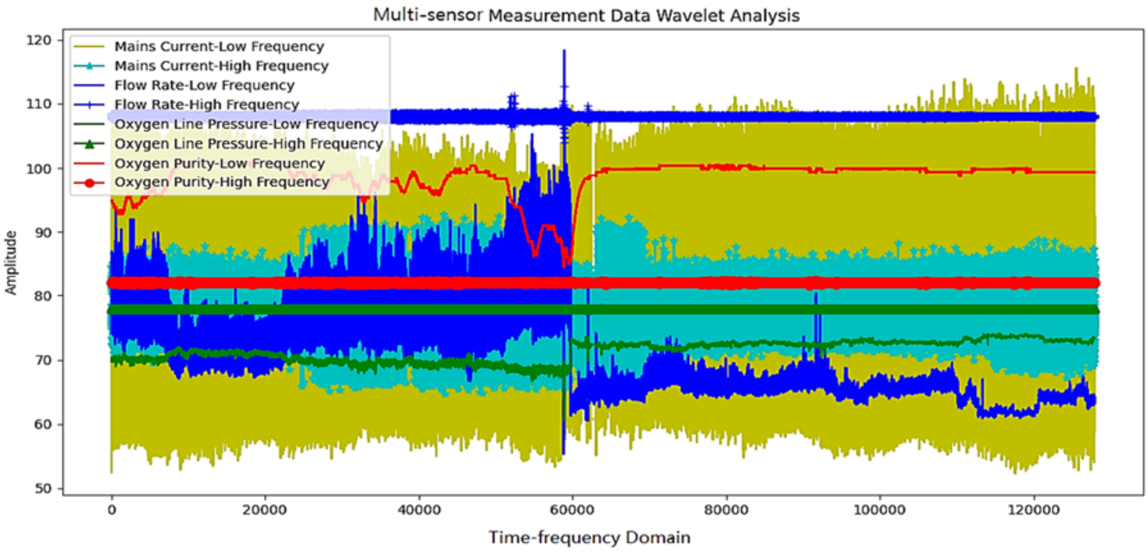

Fig. 9. Multi-sensor measurement signals in time-frequency domain.

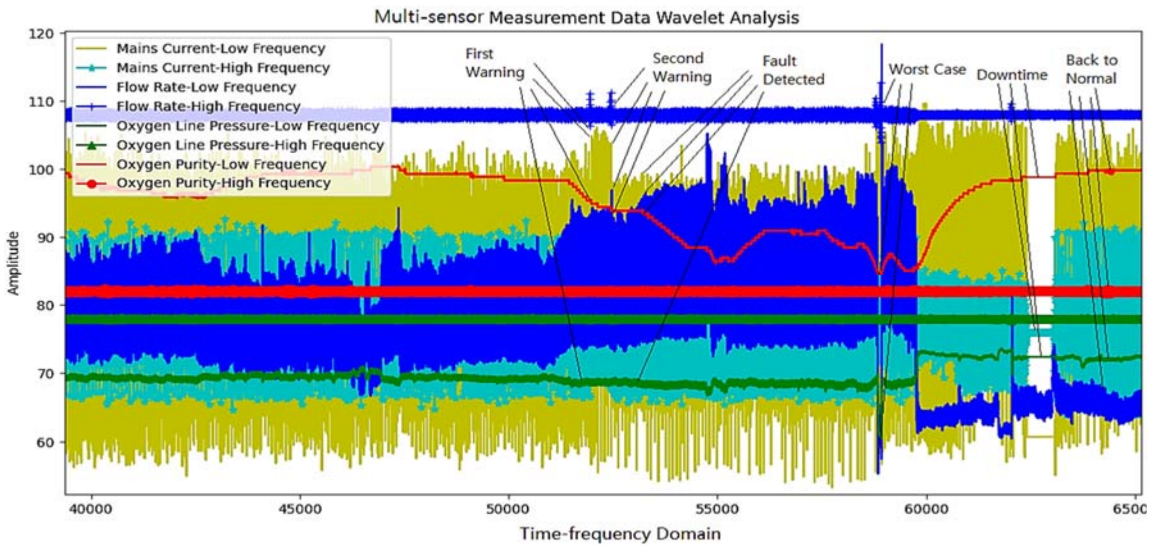

Fig. 10. Details of multi-sensor measurement signals in time-frequency domain.

As shown in Fig. 10, detailed information reflecting the change of operation conditions can be obtained in the low and high frequency components. It is noted that before faults are detected, there are two patterns that signify large changes of system conditions, at the same time, values of oxygen purity and oxygen line pressure keep decreasing. So by time, they are classified as first warning (start at data point 51948) and second warning (start at data point 52446). At data point 53284 fults are detected and triggered by low oxygen purity that is not acceptable. Then faulty condition continues and at data point 58908 it reaches the worst case when the values of oxygen purity and oxygen line pressure are both at their minimums. After that point, values of both oxygen purity and oxygen line pressure are increasing, but still conditions are not getting back to normal. At data point between 62400 and 63097, compressors stop and this is marked as downtime. Then compressors restart and eventually at data point 63856, flow rate has dropped, system is recovered and back to normal.

In faults prediction and detection, the presence of faults is verified in an unsupervised manner by abnormal/fault detection algorithms, but will be learnt and optimised later by the machine learning system. The system will also diagnose each fault and perform cause analysis based on importance ranking explained by the model library. As the extracted features can only indicate the presence of a fault, its type and cause still need to be found. While the most relevant feature that is considered as the fault present in the system, it is very often related to a potential or unique type of component fault, and also can be related to more than one fault, hence it is important to establish a human knowledge base to perform the explanability, from which the cause is analysed and error can be corrected.

For example, the above detected faults can be attributed to the high demand of oxygen at a special time, when the flow rate increased at a very high level, the system could not generate enough output due to the limited capacity of compressors and that would lead to a system failure, leading to a low oxygen purity and line pressure that were detected by the system as a fault. Before it happened, there were many features/signs that indicated the trending and thus warnings were given. This is learnt by the system so that knowledge is accumulated in the database for real-time decision-making.

Experimental results have demonstrated that by the trained DWNN with multi-sensor measurements, edge and cloud computing over the IoT communication networks, where the sensing capabilities and the computational power are provided by the designed controller, transmitter and cloud server to track everything that's relevant to operations, the real-time machine learning system can perform qualitative and quantitative data analysis to build the next generation decision support system that can monitor machine conditions, detect faults, predict and optimise system performance, action changes in a process to optimise the efficient use and operations of complex MIMO systems. Data analytics by deep learning can also help us to establish a knowledge base from which to correct errors, perform predictive maintenance procedures to prevent the failure without unnecessary interruptions, thus improve efficiency and maximize profitability.

6. Conclusions

Due to the difficulty in interpreting the multi-sensor data correctly and extracting the desired information, and the strong nonlinearity and its nearly instantaneous response to disturbances, it is still very challenging for system equipped with multiple sensors over IoT networks to achieve accurate faults prediction and optimised performance in complex multiple-input multiple-output (MIMO) systems. In this paper, the new data-driven model proposed is improving and dramatically changing the way that real-time faults prediction can be achieved through transforming the raw multi-sensor data into the time-frequency domain by developing fast lifting wavelet transform with computational efficiency to obtain a big feature vector containing all the relevant features from all of the sensors, and giving more informative signatures for faults prediction. To accurately predict and detect relevant status information of the actuators and to monitor the health status of specific components, the machine learning system developed, where the sensing capabilities and the computational power are provided by the designed controller, transmitter and cloud server to track everything that is relevant to operations, has enabled confident decision making, and faults prediction and predictive maintenance, which can be applied to coupled MIMO systems of complex industrial processes. By building IoT network to remotely collect data and developing deep wavelet neural networks (DWNN) with Gaussian (Mexican hat) wavelet derived as activation functions to improve nonlinear fitting and convergence speed, and to process the real-time data for faults prediction, data analytics can help establish a knowledge base from which to correct errors, perform predictive maintenance procedures to prevent the failure without unnecessary interruptions, thus to improve efficiency and maximize profitability.

Experimental results have demonstrated that by the trained DWNN with multi-sensor measurements, edge and cloud computing over the IoT communication networks, the real-time machine learning system can perform qualitative and quantitative data analysis to build the next generation decision support system that can monitor machine conditions, predict and detect faults, and optimise system performance, action changes in a process to optimise the efficient use and operations of complex MIMO systems.

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EEG Real Time Analysis for Driver's Arm Movements Identification

[*] Enrico Zero, Chiara Bersani and Roberto Sacile
Department of Informatics, Bioengineering, Robotics and Systems Engineering, University of Genova, Via all'Opera Pia 13, 16145 Genova, Italy
E-mail: enrico.zero@dibris.unige.it

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Abstract: Literature proved the potential benefits of autonomous vehicles in terms of road safety, traffic congestion, and energy consumption. The autonomous vehicles must be supported by advanced sensors and technologies to build reliable awareness of the external environment. However, cars with different levels of automation entail different levels of human intervention during the driving tasks. In this context, the main issue is to determine the interaction between the human and the automated driving system which requires an exhaustive understanding of the driver behavior above all in critical situations. This paper presents a neural network-based classifier of EEG signals to identify the driver's arm movements by his/her brain electrical activities, when he/she must steer to perform a right or a left turn on a curvilinear trajectory. The classifier based on a time delay neural network (TDNN) aims to classify the human's EEG signals when the participant executes the action to move his/her arms gripping a real steering wheel while driving in a simulated environmental. The performances of the classifier related to the recognition of the driver's arm movements by the brain signals demonstrated promising results that are worthwhile to be further explored.

Keywords: EEG, Identification, Neural network, Autonomous vehicles, Safety.

1. Introduction

In the automotive context, research and innovation have recently focused on the realization of self-driving vehicles. Autonomous Vehicles (AV) refer to car which can detect the environment by devices and sensors installed on board and to drive with a limited or without human intervention. According to the SAE International Standard 0, AVs are classified in six different levels of automation, from level 0 where the driver is the only decision maker to the forthcoming level 5 where the vehicle is completely managed by the automated driving systems (ADS). In detail, at level 0, the driver performs all dynamic driving tasks (DDTs) which consist in the tactical and operational functions required for the vehicle motion. Level 1 is applied when the ADS performs the DDTs related to either the longitudinal or the lateral vehicle motion control. At level 2, the ADS performs, simultaneously, both the longitudinal and the lateral vehicle control. At level 3, the ADS also performs the Object and Event Detection and Response (OEDR) to identify and to avoid events or obstacles on the route. At level 4, the ADS also completes DDT fallback 0. This function consists in a higher automation equipment which may intervene when the ADS fails in case of risk conditions. In the low levels of automation (Level 0 to Level 2), the driver is considered present and essential to compute part of the main DDTs. In the level 3, the driver may assist the ADS when a failure occurs during a trip, while at the level 4, the ADS performs overall function included the DDT fallback. Level 5 is reached when the vehicle is fully autonomous without the human user's intervention.

To detect and to identify the external environment, the ADS must recognize in real time the road shape, road signs, and the different objects on the road 0. For this reason, the AV must be equipped with specific sensors such as camera, Radar or Light Detection and Ranging (LiDAR) 0. The recent technological advances in the image treatments provides object-detection models based on multiclass problems where the different elements which can appear on the road may be recognized. In 0, a 2D object detection model for vehicles, pedestrian and cyclist identification is proposed. The authors compared both one and two stages deep learning techniques to process images with different resolutions to identify the method which generates the best trade-off between speed and accuracy for the detection system. In 0, the authors proposed a radar-based deep neural network (DNN) to recognize road segmentations when the different objects such as road-users, obstacles, and other obstructions are present on the street.

So, the use of radar and camera fusion algorithm provides better performances in respect to one sensor application above all in severe environmental condition 0. The LiDAR represents the main expensive solution among the detection systems whether, due its high resolution, is also the most adequate, above all, for SAE level 4 and 5. The 3D LiDAR provides images and measurements not affected by sunlight and different classifier have been tested for the real time obstacle detection. Among others, support vector machine (SVM) is used in 0 to recognized in real time vehicles on an urban context while a convolutional neural network has been adopted to classify vehicle lane change through LiDAR-based environment analysis 0.

1.1. EEG Based Driver Behavior Detection

In AVs at level 5, the driver is completely absent in the decision framework. To reach this condition, the vehicle must drive in an autonomous way. A propaedeutic analysis of the driver behaviour must be carried out to define the traditional driving style and to identify the relationships between the automated and non-automated driving system in order to implement the control commands at the operational level. In literature it is demonstrated that the physical and neurological driver's state affects the driving performances 0. The physiological state of the driver may be detected by different modalities based on the electrooculogram (EOG), the functional magnetic resonance imaging (fMRI), the high-frequency electrocardiogram (ECG) or the electroencephalography (EEG).

Driver's fatigue and distraction represent the major causes of accidents and crashes. In 0, the EOG, which detects the electrical signal generated by eye movements, is acquired, and processed by the fusion technique to identify driver's drowsiness. The fMRI identifies changes in cerebral oxygenation during cognitive tasks and it is used to demonstrate the correlation between brain activation and simulated driving actions 0. In a similar way, in 0, the authors applied a functional near infrared spectroscopy (fNIRS) to quantify variations in cortical activity related to changes in workload during driver tasks. Several studies monitored the heart rate variability to extract significant features related to driver drowsiness 0, driver workload 0 or sleepiness 0.

The EEG monitoring refers to the acquisition of brain signals from the different lobes of the brain in order to identify the cerebral waves variations when the subjects perform cognitive task. The EEG signals represent one of the main promising and reliable physiological indicators to describe human state 0. The EEG recording is often used to evaluate driver attention 0, fatigue 0, mental state 0 or, in general, cognitive response in driving environment 0. More recently, the EEG signal acquisition has also been used to identify the human intention for movements. The main objective of this research field, in the context of the AV, is to extract the main features from the EEG signals while the driver performs a specific movement and to classify the brain activities as belonging to the subject's intention to move the related part of his/her body.

Traditionally, the EEG device and the classification algorithm are coupled to a Brain Computer Interface (BCI) system. The EEG based BCI provides the possibility for the user to command an external device through the brain electrical signals according to his/her intention. In other words, the EEG acquires the cerebral signals, the classifier interprets the human movement intentions by the brain activities and finally the BCI translates them into a command for the devices. An EEG based BCI may represent a novel sensor and transducer tool to identify the main parameters of a human movements such as speed, direction, and force 0. Special interest has been given to the classification of hands 0, fingers 0, and eyes movements 0. In 0, a review about detection of movement intention using EEG signals appears.

Although the EEG based BCI may be a significant improvement in the realization of tools which assist the driver to prevent accidents, limited literature appears in the context of arm movements identification. In 0, the authors developed a classifier based on the support vector machine (SVM) to classify three classes of driver movements, left, right and brake. By the proposed approach, the authors obtained to predict the driver's action 500ms earlier with an accuracy of 94,6 %. Also, in 0, SVM and convolutional neural networks (CNN) are applied to EEG signals acquired during a breaking action to detect pedal pushing and to discriminate between driver's intent to brake in emergency condition and in the normal state of driving. In those experiments, the average accuracy reaches about 71 %. In 0, the authors used EEG signals and waveband specular meteor radar (SMR) to monitor drivers' physiological state and eye-movement electrical waves to identify the relationship between driver fatigue states and driver's grip force on the steering wheel while driving.

More recently, the EEG based BCI are used in the closed loop to establish a communication to external devices and send command inputs to them. Furthermore, imagined movement decoding methods are successfully used to classify horizontal and vertical movements of the right arm using EEG 00. In 0, the authors implemented a quadratic discriminant analysis (QDA) method to generate a classifier tested to regulate the motion of brushless DC motor used in neuro-aid engineering application. In this case, two classes are identified from EEG features to move the motor in clockwise and anticlockwise directions. Similar applications based on EEG signals for motor imagery classification appear in literature related to hand prostheses 0, wheelchair 0 or quadcopter 0. A wide review on robot controller by motor imagery BCI appears in 0.

This paper is inspired by 0 where a preliminary EEG based BCI is used to classify the arm movements of a driver who must rotate the steering wheel to perform a right or a left turn to execute a curve in a virtual driving environment. The main objective of this work is to increase the number of participants and extend the experiment results in terms of accuracy and reliability.

2. Material and Methods

This work focuses on a specific approach which aims at identifying and classifying the driver's arm movements according to the data coming from the electroencephalography. In general, EEG systems are categorized as invasive and non-invasive. The first one included electrodes which have to be implanted inside the cranium while, in the second case, the electrodes may adhere to the scalp. In this work, the non-invasive solution is adopted.

2.1. Enobio EEG Cap

The experiments have been performed by using the Enobio Cap 8 Features. Signals were recorded at 500Hz from six different channels, namely F7, FZ, F8, C4, C3, CZ, in accordance with the international 10-20 system. The selected channels are shown in the Fig. 1.

The electrodes are located on the medial premotor area and on primary motor cortex.

2.1.1. Driving Test

The driving simulator consisted in two different components. Firstly, a common chair is positioned in front of an LCD screen which projected the driving simulated environment. Besides, the user is also provided with a steering wheel connected to the pedal system to perform real movements for turning and breaking.

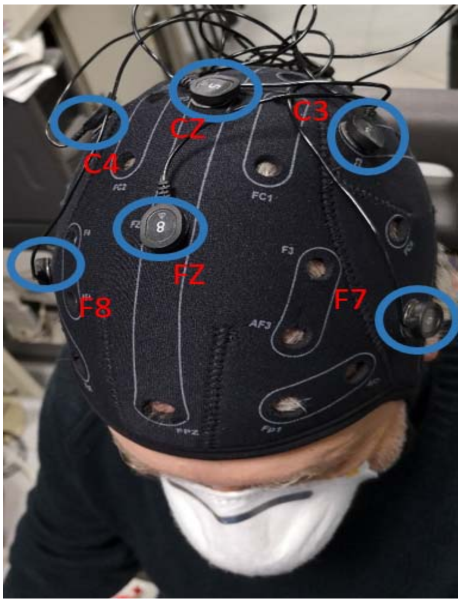

Fig. 1. Electrodes placement in the ENOBIO cap. (Blue circles represent the electrodes monitored during the experiments).

The set of subjects includes 3 participants who are, respectively, 25, 26 and 30 years old with driving license. Each participant performed three times the proposed test. The driver could rotate the steering wheel, accelerate or brake as if he/she were driving a real car. Each simulation lasted 15 minutes and, the user had to drive along a tour represented by the Fig. 2.

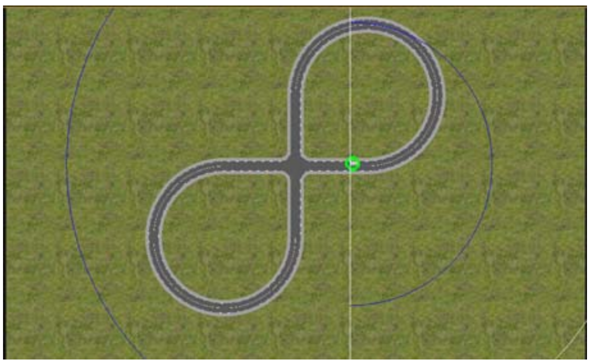

Fig. 2. Test drive circuit in OKTAL Simulator environment.

In each test, each driver run almost eight times on such route. OKTAL Scanner Studio is the software used to generate the simulation environment. The focus of this paper is to study the correlation between the arm movements of the driver while performing the right/left curves on the road and the related recorded EEG signals.

2.2. Preprocessing Data

The elaboration data was performed in Matlab R2020b. A high pass filter to 0.167 Hz was applied to the EEG signals to remove the direct current shift. Three different analyses have been realized by the implementation of time delay neural network (TDNN). TDNN has been used due to its capability to generate a finite dynamic response to time series input data.

The TDNN is typically successfully used in complex input-output identification but its large application in EEG signal analysis has been verified due to the non – stationary nature of the brain activities 0. In 0 the TTDN is applied for the classification of finger movements with a recognition rate of 93.02 %.

The TDNN performed in this paper, whose structure is presented in the Fig. 3, has 10 time delays and 4 hidden units.

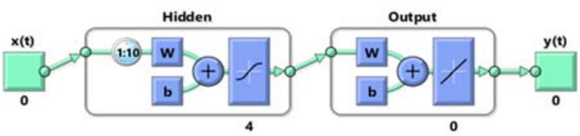

Fig. 3. TDNN used in the paper.

2.3. Experiments

The experiment involved 3 measurement sessions for each participant, once in three different days. In the following, the data are identified by the participant ID, P1 or P2 or P3, and by the training sessions chronologically numbered as 1, 2 or 3. Three different analyses have been carried out on the monitored EEG signals.

2.3.1. First Analysis

The first test is related to the classifier generation by the Levenberg Marquardt algorithm based TDNN. The data acquired in each session for each participant was divided in two an equal number of samples, labelled as 1A, 1B, 2A, 2B, 3A, 3B. The different sets of data have been used to train and test six TDNNs in order to identify the best classifier in term of correlation.

In Table 1, the different training and test datasets used in the applications appear.

Table 1. Set of data used to train and test the TDNNs in the first analysis.

TDNN	Training set	Test set
NN1	1A	1B
NN2	2A	2B
NN3	3A	3B
NN4	2A, 2B, 3A	3B
NN5	1A, 1B, 2A	2B
NN6	1A, 1B, 2A, 2B, 3A	3B

The generated NNs listed in Table 1 have been realized for each participant creating 18 TDNNs (6 NNs for the three participants). The main objective of the first analysis is to evaluate if the increasing number of input data in the training phase may reflect a better recognition performance.

2.3.2. Second Analysis

In the second test, the TDNNs, obtained in the previous test, have been modified. In particular, the NN4, NN5 and NN6, for each participant, have been revised by modifying the cost function which minimizes the Mean Square Error (MSE). In this second approach, a weight p_i has been introduced, for each sample which belongs to the training set, in the objective function as in (1).

$$MSE = \frac{1}{N * S}\sum_{k=1}^{S}\sum_{i=1}^{N} p_i^s \,(y_i^s - \hat{y}_i^s)^2, \qquad (1)$$

where:
MSE =mean square error;
S = number of dataset *s-th* used in the training;
N = number of elements in each dataset *s-th* used in the training set;
p_i^s = weight associated to each data *i-th* belonging to the dataset *s-th*;
y_i^s = observed value of the output in the dataset *s-th*;
$\hat{y}_i^s$ = predicted value for the output in the dataset *s-th*.

The new TDNNs, namely NN7, NN8 and NN9, are trained and tested by the same data set already adopted, respectively, in NN4, NN5 and NN6 for each participant. However, in this new approach, the objective functions for the training phase have been modified balancing the different input components as appear in Table 2. Note that the data coming from the older tests have lower weights with respect to the recent ones.

Table 2. TDNNs characteristics.

TDNN	Dataset *s-th* in the objective function	Weights p_i^s	Test set
NN7	2A	0.5	3B
	2B	0.5	
	3A	1	
NN8	1A	0.5	2B
	1B	0.5	
	2A	1	
NN9	1A	0.25	3B
	1B	0.25	
	2A	0.5	
	2B	0.5	
	3A	1	

The aim of the second analysis is related to identify the set of parameters which, by multiplying the objective components, increase the accuracy of the recognition.

2.3.3. Third Analysis

The non-linear characteristics of the neural network function may keep the results to be sensibly different according to the initialization of the weights present in its units. The third test has been carried out to evaluate TDNN performance variations according to different initializations of the values of the weights related to the layers of the neural network, calibrated or randomized.

Specifically, the performances have been evaluated comparing the TDNN recognition accuracy and the computational time required by the identification process, when the TDNN weights are randomly initialized by the system versus the TDNN weights initialized with values obtained from previous training sessions.

More specifically, in the latter case, values are calibrated according to the values obtained as output of the training phase for the TDNNs specified in the Table 3, column "Initialization of the weights of TDNN layers". The columns "Training set" and "Test set" list, respectively, the dataset used to train and test the related NN in the row.

To explain better the approach, an example is presented. In the case of NN17, a standard TDNN has been created by a specific training on the samples 1A,1B, 2A related to the first and second sessions of experiments for the same participant. Then, the generated NN17, where the weights are initialized according to this first training phase, has been trained again on the subset 1A, 1B, 2A, 2B and tested on the subset 3A.

On the other hand, the NN16 is trained and tested with the same dataset of NN17 but without specific values of the weight parameters.

3. Results

Results are evaluated against two main indicators, *MSE* and *R*, which is the correlation coefficient of the predicted versus the actual values.

A preliminary analysis about the values for *R* and the *MSE*, for the TDNNs generated for the three participants is displayed in Table 4.

The results demonstrated that the *R* value, averaged over the three participants for the overall generated TDNNs, is close to 0.5. Also, the *MSE* values represent promising results in terms of reliability for the proposed approaches.

Table 5 shows the *R* index of each TDNN in the first analysis for the second participant (P2).

The results show a sensible good correlation between the EEG signals and the actual arm movements of the participant. In three cases, R is greater than 0.6.

From Table 1, it is possible to note a growing number of datasets used to train the NNs, from NN1 to NN6. However, by the results in Table 5, the increasing number of input data for the training phase does not reflect a significant improvement of the performances in terms of *R* and *MSE*.

Table 3. Generation of the weights used in the TDNNs.

TDNN	Initialization of the weights of TDNN layers	Training set	Test set
NN10	weights generated by 1A, 1B, 2A, 2B	3A	3B
NN11	weights generated by 1A, 1B	2A	2B
NN12	random weights	1A, 1B	2A
NN13	weights generated by 1A	1A, 1B	2A
NN14	random weights	1A, 1B, 2A	2B
NN15	weights generated by 1A and 1B	1A, 1B, 2A	2B
NN16	random weights	1A, 1B, 2A, 2B	3A
NN17	weights generated by 1A, 1B, 2A	1A, 1B, 2A, 2B	3A
NN18	random weights	1A, 1B, 2A, 2B, 3A	3B
NN19	weights generated by 1A, 1B, 2A, 2B	1A, 1B, 2A, 2B, 3A	3B

Table 4. Mean values of the performance indices computed for each TDNN averaged over the three participants.

TDNN	R	MSE
NN1	0.6812	0.4310
NN2	0.7001	0.4709
NN3	0.5603	0.5797
NN4	0.5818	0.5077
NN5	0.5348	0.6099
NN6	0.3836	0.6597
NN7	0.5950	0.5102
NN8	0.5774	0.5726
NN9	0.5364	0.5570
NN10	0.5811	0.5529
NN11	0.6316	0.5285
NN12	0.1001	1.0378
NN13	0.3802	0.8660
NN14	0.3917	0.7167
NN15	0.5169	0.6356
NN16	0.2713	0.7666
NN17	0.2132	0.8039
NN18	0.4379	0.6480
NN19	0.4075	0.6453
Mean	**0.48**	**0.64**

Table 5. First analysis results for P2.

TDNN	R	MSE
P2_NN1	0.6628	0.3838
P2_NN2	0.6610	0.4506
P2_NN3	0.5492	0.6213
P2_NN4	0.6435	0.4174
P2_NN5	0.2773	0.7922
P2_NN6	0.2907	0.7383

In the second analysis (Table 6), a stronger correlation is verified in the P2_NN7. Besides, the modified objective function produces better values, both for *R* and *MSE*, in the P2_NN8 versus the P2_NN5 and in the P2_NN9 versus the P2_NN6. In fact, respectively, the couple of NN5 and NN8 and the couple NN6 and NN9 are trained and tested by the same dataset for each participant but with different weight p_i^s (see Table 1 and Table 2).

In the third analysis, reported in the Table 7 related to the participant P2, the recognition accuracy for TDNNs initialized randomly or with accurate weights input values, appear very similar. The different approaches to initialize the layer parameters are not significant in terms of prediction. However, from the computation viewpoint, the TDNNs with accurate custom initialization appears, in general, less time expensive in respect to the ones with random initialization.

The three analysis are performed for the other two participants and, in the Table 8, the results regarding the first analysis in the first participant (P1) are reported.

Table 6. Second analysis results for P2.

TDNN	R	MSE
P2_NN7	0.6356	0.4363
P2_NN8	0.4851	0.6200
P2_NN9	0.4197	0.6080

Table 7. Third analysis results for P2.

TDNN	R	MSE	TIME (sec)
P2_NN10	0.6234	0.5489	47.0743
P2_NN11	0.4943	0.5873	34.6633
P2_NN12	0.2824	0.7039	241.2782
P2_NN13	0.4214	0.6526	205.9559
P2_NN14	0.1913	0.8688	451.9295
P2_NN15	0.3794	0.7182	185.1008
P2_NN16	0.3053	0.6668	418.4075
P2_NN17	0.0687	0.8356	276.9772
P2_NN18	0.3793	0.6414	245.0443
P2_NN19	0.1547	0.7996	583.0464

Table 8. First analysis results for P1.

TDNN	R	MSE
P1_NN1	0.8159	0.3657
P1_NN2	0.8538	0.2828
P1_NN3	0.6079	0.5130
P1_NN4	0.6486	0.4528
P1_NN5	0.8507	0.292
P1_NN6	0.6588	0.4622

For the first analysis, higher correlation is obtained in respect to the results reported for the P2. In this case, the value *R* is higher than 0.8 for NN1, NN2, and NN5.

In detail, Fig. 4 shows the comparison between the values related to actual angle associated to the rotation of the steering wheel realized by the participant during the simulation and the predicted values generated by the NN2 related to the direction of the arm movements. The graph highlights a significant overlapping of the peaks (values -1 and 1) associated to the correct prediction of the driver's arms movement on right and left.

The results related to second analysis regarding participant P1 are displayed in Table 9.

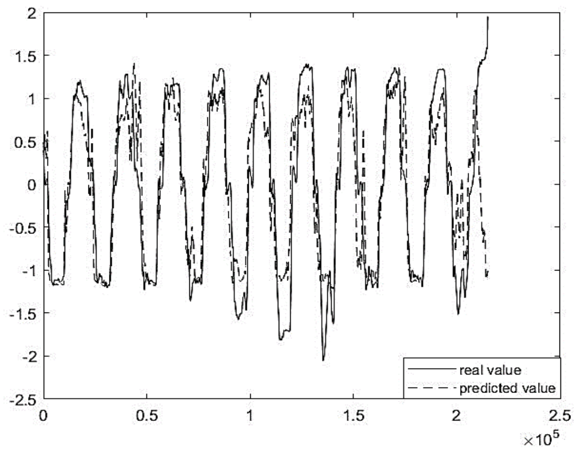

Fig. 4. Predictive and real value in P1_NN2.

Table 9. Second analysis results for P1.

TDNN	R	MSE
P1_NN7	0.6408	0.4633
P1_NN8	0.8502	0.2892
P1_NN9	0.6442	0.4464

In this case also, the *R* value is higher than 0.64 demonstrating a good correlation among predicted and actual data. On the contrary, the modified objective function does not introduce any positive variation in terms of prediction accuracy. The third analysis for P1 is reported in the Table 10.

Table 10. Third analysis results for P1.

TDNN	R	MSE	TIME (sec)
P1_NN10	0.6040	0.4949	100.052
P1_NN11	0.8517	0.2864	24.882
P1_NN12	0.4501	0.8698	114.260
P1_NN13	0.4696	0.7928	54.245
P1_NN14	0.8542	0.2854	196.969
P1_NN15	0.8495	0.2912	567.360
P1_NN16	0.5545	0.6188	442.865
P1_NN17	0.5983	0.5841	127.593
P1_NN18	0.6056	0.5841	209.203
P1_NN19	0.6392	0.4781	644.334

In this analysis, the *R* value is greater than 0.5 for 80 % of tests, while the *MSE* is lower than 0,5 for the 50 %. In general, anyway, we can conclude that the initialization of the weights for the neural network layers is not substantial in terms of accuracy of prediction in respect to the NNs randomly initialized.

4. Conclusions

This work aims at implementing a TDNN based classifier of EEG signals for driver's arm movements recognition.

This study is motivated by two principal purposes. Firstly, the driver's style recognition is crucial in the driving safety in order to prevent accidents and to react to critical situations. Secondly, the identification of the driver's behavior during specific driving tasks may support the understanding of the relationship between the driver and the automated driving systems (ADS), above all, in AVs at level 3 and 4.

The principal contribution of this paper is related to the development of a classifier for driver's arm movements recognition using EEG signals when the user rotates the steering wheel in order to perform a turn in a driving simulated scenario. The EEG data acquired by a non-invasive EEG cap, whose electrodes are in contact with the scalp, have been processed to classify those movements according to three classes: right or left turns and central position.

Moreover, three different methods have been implemented to evaluate possible improvements in the quality of the accuracy for the driver's arm movements prediction.

Firstly, the TDNNs generated for the recognition of movements have been modified by increasing the number of the datased used to train the NNs. In the second approach, the different components of the objective function have been differently weighted in order to minimize the MSE. Finally, the initialization of the weights associated to the layers of the neural network has been introduced to evaluate possible benefits in respect to the traditional random initialization.

Results demonstrated a statistically significant positive correlation of the EEG signals with the actual participant's actions to realize a turning in a car which cover a curvilinear path in a simulated environment. On the contrary, the proposed approaches to increase accuracy of movement's prediction do not assume specific relevance in the proposed experiments. So, due to the complexity of the problem and the relevance of the first preliminary analyses, this study merits to be further explored increasing the number of participants and evaluating new techniques for the classifier implementation.

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A Survey on Applications of Human-Robot Interaction

Abdel-Nasser Sharkawy
Mechatronics Engineering, Mechanical Engineering Department, Faculty of Engineering,
South Valley University, Qena 83523, Egypt
Tel.:+20-1001689823
E-mail: eng.abdelnassersharkawy@gmail.com

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Abstract: Human-robot interaction (HRI) is the extensive research topic which aims at the complementary combination between the robot capabilities and human skills. The robots assist humans in terms of precision, speed, and force. The humans contribute in terms of the experience, knowledge of executing the task, intuition, and easy adaptation and learning, and understanding of control strategies. In this manuscript, a survey on the applications of HRI is presented. These applications could be industrial, medical, agricultural, servical, and educational. HRI can be found in industrial applications in handling of the workpieces in the production lines, co-manipulation tasks, welding processes, parts assembly, and painting. Assistive robotics are one from the highest profile areas in HRI. For people with the physical and the mental challenges, the robots can provide the opportunity of interaction and therapy. Furthermore, HRI can be widely applied in hospitals. Nowadays, HRI is very important to fight against the new coronavirus (COVID-19) pandemic. In agriculture, the robot is able to help humans with many tasks such as harvesting, seeding, fertilizing, spraying, weed detection, hauling, and mowing. HRI is quite new in the field of education. However, the robot can help children in classrooms for learning processes. In addition, the robots can help young children empathy and social skills. HRI can be found in other applications such as home use, inventory management, mining, Space exploration, and UAVs.

Keywords: Human-Robot interaction, Industrial applications, Medical and Rehabilitation applications, Precision agriculture, Education.

1. Introduction

HRI is the field of the study referring to understanding, designing, and evaluating the robotic systems used by or collaborating with the human operator. Interaction needs the communication between the robots and the humans. The human communication with the robot could take many forms. However, these forms are highly affected by whether the human operator closeness to the robot. Therefore, the communication or interaction between both the human and the robot is separated into two main categories [1-2]. The first category is the remote interaction and the second is proximate interaction. In the remote one, the human does not exist in nearby the robot. In addition, they are spatially or even temporarily separated. An example for this category is the Mars Rovers which is separated from earth in space and time as well. In the proximate category, the human and robot coexist in the same location. An example for this category is the service robots during their sharing with the humans in the same room.

These categories can help distinguish between the applications requiring the mobility, physical interaction, or social interaction. Remote interaction using mobile robots refers to the tele-operation or the supervised control. Remote interaction using the physical manipulator refers to the tele-manipulation.

Proximate interaction using the mobile robots takes the form of the robot assistant. Proximate interaction includes the physical interaction. In social interaction, the social and the emotive as well as the cognitive interaction aspects are included. In social interaction, the humans and the robots interact using the form of peers or companions. Importantly, social interactions with the robots take the form of proximate interaction rather than remote interaction.

From these categories, this manuscript deals with the proximate interaction. This manuscript is an extension to our previous paper [3]. It presents some real applications for HRI in industrial environment, medical and rehabilitation, agriculture, education, and other environments. Basically, these applications show the importance of the interaction happening between the robot and human operator in the real life.

The rest of this paper is divided as follows. Section 2 presents the industrial applications of HRI. In Section 3, the HRI in the medical and rehabilitation applications is presented. HRI in agriculture is demonstrated in Section 4, whereas Section 5 illustrates the HRI in education. Section 6 discusses some other applications of HRI. In Section 7, some methods for improving the HRI are discussed. Improving HRI leads to achieving the tasks and the applications easily and efficiently. In final, Section 8 concludes the main important points of this manuscript.

2. HRI in Industry

HRI is widely used in industrial applications such as picking and placing in the production lines, welding processes, parts assembly, painting, and so on.

Some examples for HRI in the industrial application are presented from Fig. 1 to Fig. 4. The robot workstation is running in the plant of BMW in South Carolina in which the robot helps human operators to perform the assembly of the final door [4] (see Fig. 1). In the door assembly operation, human operator and robots work together. BMW plant has succeeded to implement and develop the direct human-robot cooperation and interaction in the series production.

Human-robot teams are found also in the flexible production lines [5-6], as presented in Fig. 2. In this figure, the robotic manipulators and the human operators collaborate in handling of the workpieces. Safety is also is very important in such environments, since the proximity of the human operator to the robot that can lead to potential injuries.

In [7-8] a load of 1 kg is mounted to KUKA LWR robot end-effector to simulate a real case of transferring an object from place to place. The KUKA robot and the human operator are collaborating to transfer this object. In this case, the human hand guides the robot end-effector along a straight line segment motion via a variable admittance controller. This variable admittance control achieved higher reduction in the required human effort and the task completion time as well as higher increase in the achieved accuracy. This case is presented in Fig. 3.

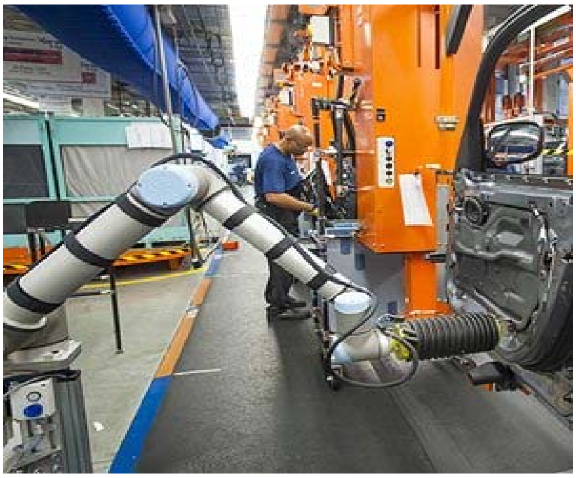

Fig. 1. The robot helps the human to perform the final door assembly in the BMW plant [4].

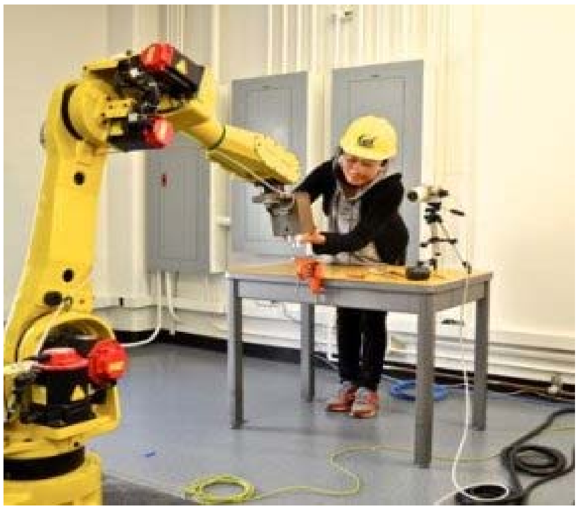

Fig. 2. The robot and the human workers cooperate in handling workpieces [5-6].

Fig. 3. The KUKA LWR robot and the human operator are collaborating to transfer an object (1 kg) [7-8].

Repetitive co-manipulation tasks as shown in Fig. 4 [9] can be performed in suitable poses of the human body. These poses can minimise the effects of the overloading joint torque. Furthermore, they can maximise the capacity of the manipulation of the human.

Another simple co-manipulating task is presented in Fig. 5 [8, 10]. In this task, the human arm and the manipulator are modelled as a closed kinematic chain (CKC). The selected task is a straight motion in which the robot end-effector is guided by the human operator via a constant admittance controller. The best location of the selected task is determined by the maximization of the minimal manipulability of the CKC along the path. The results from this approach succeeded to achieve the high velocity of the robot and the high human comfort, but in expense of the achieved accuracy.

Fig. 4. Example for the repetitive co-manipulation tasks [9].

Fig. 5. A simple co-manipulation task in which the best location of both the human-arm and the robot is determined [8, 10].

For handling of heavy and bulky components in welding situations, the multi-robot system with collaborative functionality assists the worker [11], as shown in Fig. 6. Two robots help position the components to be joined in the welding process, at which point the human operator carries out the welding task under favourable ergonomic conditions. In comparison with the standard welding bench, the human operator does not need to assume the uncomfortable postures or the work overhead. All necessary positioning and orientation of the workpieces can be performed by the robot. This also includes presenting of the components in the optimal position for the process of welding, allowing proper flow of the welding bead. Since the robotic repositioning motion is quite fast, the handling time which is about one third of the total process time is reduced to a minimum in comparison to welding processes in which HRI is not implemented.

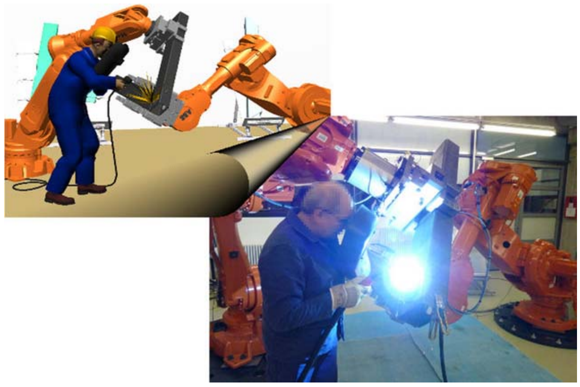

Fig. 6. The multi-robot system assists the worker in the welding process [11].

3. HRI in Rehabilitation and Medical Applications

Assistive robotics are one of the highest profile areas in HRI. For people with the physical and the mental challenges, robots can provide the opportunity for the interaction and therapy. This work is explored with autistic children in ref. [12, 13]. Many of them cannot respond strongly to the social cues but they respond very well to the mechanical devices. Robots give the possible therapeutic role for using the mechanical device for improving the social interactions [14]. Robots are being considered also for different domains in which children benefit, for example, children with experienced trauma. The social dimension of human-robot interaction is necessary not only in the assistive roles, but also in many areas and domains of the proximate interaction [15-19].

For people with physical disabilities, the robot embodiment provides the unique opportunities which are not possible with other technology forms. For example, the researchers are working on the design of the robots which provide and give the support for the physical therapy. Efforts include the providing of the prescribed force and the movement trajectories to help rebuild flexibility as well as strength [20]. Other work for detecting the motivational state and adjusting the therapy in order to maximize the benefits is presented in ref. [21]. Intelligent wheelchairs are the type of the robot which use the external sensors for supporting the path planning and the collision avoidance for the person that requires the wheelchair [22, 23].

An example of the rehabilitation robotics was presented in [24], in which, a robotic system was built as shown in Fig. 7, that performs correctly the exercise for the conventional physiotherapy such as the shoulder flexion, in similar way to what the physiotherapist do during the co-manipulating with KUKA LWR robot. In this way, the excellent characteristics of the human (the capacity of the decision, experience) and the robot (the precision, the work capacity, the speed, the force, and the repeatability) could be combined to achieve better results in the musculoskeletal rehabilitation of the arm. Furthermore, the second as well as the main objective was evaluating the non-pathological shoulder behaviour while performing the shoulder flexion movements.

Fig. 7. An Example illustrates the rehabilitation robotics [24].

The service or collaborative robots can take initiative to participate with nurses in decision making [25]. Based on that, Gombolay, *et al*. [25] conducted a successful test demonstration in which a robot assists the resource nurses on the labor and delivery floor in the tertiary care center (see Fig. 8). Furthermore, medical service robots can provide companionship for reducing the isolation felt by many older people [26]. In one study [27], a robotic companion was more successful than a regular plush toy at helping dementia patients communicate with their families.

Coronavirus disease (COVID-19) is the infectious disease which is caused by the newly discovered coronavirus. The severity of COVID-19 symptoms can range from mild to severe. The cooperation between the human and the robot help to fight against the new pandemic.

Two cases of the human-robot cooperation can be used in the hospital to fight against Coronavirus. The first can presented as follows. The robot can add the solution to the nasopharyngeal swabs from the patients for detecting the coronavirus genetic material [28]. The KUKA robot is used in the laboratory for making the tests (see Fig. 9), which greatly simplifies the test procedure. The positive test result illustrates that the patient is infected with the coronavirus. In that case, the samples which are taken from the patients' mouth, nose, and throat are tested for the genetic material of the coronavirus in the laboratory. The staff of the laboratory must only load the samples into the tray and then the COVID-19 test robot takes care with the pipetting.

Fig. 8. The robot system in action on the labor floor [25].

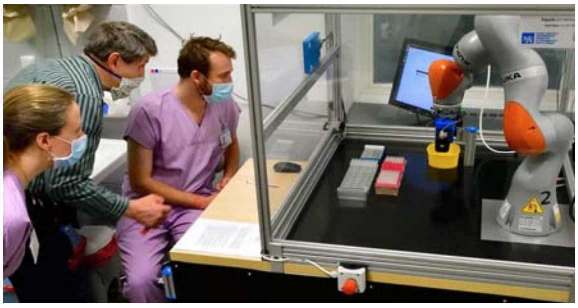

Fig. 9. The laboratory staff load the samples into the tray and the COVID-19 test KUKA robot takes care with the pipetting [28].

In the second case, a mobile unit is provided to the manipulator, as presented in Fig. 10. The mobile robot works hand in hand with the human and align to the workpiece with high precision.

Fig. 10. Mobile robot from KUKA [29].

The mobile robot can be used for providing the patients with the food and medicine. In addition, the robot can measure the temperature of the patients. This would minimize the direct contact between the patients and medical staff and others, and therefore, minimizes the infection potential. The robot can also help the humans for sweeping and washing the floors and the walls. This also minimizes the virus infection.

4. HRI in Agriculture

HRI strategies in agriculture are able to provide solutions to many complex problems, providing the security, the comfort, the lower workload, and also the better process productivity [30]. The cooperation between human and robot in agriculture helps with many tasks such as harvesting and picking, pruning, seeding, fertilizing, spraying, weed detection, hauling, mowing, phenotyping, and sorting and packing.

In the precision agriculture as presented in Fig. 11 [31], the robot helps the human-operator or farmer in picking the strawberry. In that case, safety between the human operator and the robot must be included. Furthermore, the robot was controlled remotely by a co-located operator. Their task was to navigate the robot to the location of pickers when they requested it, allow the filled crates to be loaded onto the robot, and then transport these to the storage facility. In Fig. 12 [32], intelligent robot is installed in the greenhouse to care and help farmers for the melon harvesting.

(a) (b)

Fig. 11. The Thorvald robot in the evaluation environment interacting with the pickers: (a) in the open strawberry fields, (b) in the polytunnel environment [31].

Fig. 12. The robot is installed in the greenhouse for helping the farmers for harvesting the melon [32].

Guy Coleman, a precision weed control scientist from University of Sydney, has designed a robot to help farmer for the weed recognition and control [33]. This robot might have application in broadacre agriculture. This designed robot has off-the-shelf sensors and the imagery equipment set up for targeting and identifing the weeds. This robot is presented in Fig. 13.

In Scaffold Mode, the concept of HRI is observed clearly. The human operator and the robot work as a collaborative unified system in which the vehicle autonomously navigates along the structured trees rows whereas the humans on the vehicle concentrate on performing and doing some activities such as 1) thinning, 2) pruning, 3) harvesting, 4) tying trees to wire. Tree trimming tasks were presented with Bergerman, *et al*. [34] and Freitas, *et al*. [35] (see Fig. 14) in which the humans working on the robot in the Scaffold Mode were able to trim trees more than twice as fast as humans using the traditional approach based on ladder.

Georgios Adamides in [36] developed an interface which allows the human operator for teleoperating a targeted pesticide-spraying robot, as presented in Fig. 15. This interface can command the robot to navigate along the vineyards rows. The proposed autonomy level is a semiautomatic teleoperation, which implies that the robot can work autonomously and remote manually if necessary.

Fig. 13. A designed robot to help farmer for the weed recognition and control [33].

Fig. 14. Human operators performing the tree trimming while standing in a robot [34, 35].

Fig. 15. The Agricultural robot sprayer [36].

5. HRI in Education

HRI is also effective and important in the field of education. The robot can help children in classrooms for different learning processes. The robot is used for promoting the education for the typical children, whether in the home or in the schools [37, 38]. Furthermore, the robots can help the young children empathy and social skills.

Caitlyn Clabaugh and her team [39, 40] developed the socially assistive robot (SAR) tutoring system (Fig. 16) for supporting the educators efforts to teach the number concepts to the preschool children. This system was designed iteratively with the input of the education experts for being developmentally appropriate. The system was investigated and tested in the real-world preschool classroom. The collected data were used for training personalized models of the number concepts learning, leveraging the multimodal data, domain knowledge, and also learning style.

The teaching assistant robot can help teachers as an educational media in class, and a classmate of the children for English learning (see Fig. 17) [41]. Basically, this can be accomplished with children in pre-school and elementary school.

Fig. 16. The tutoring system using robot for supporting the educators efforts to teach the number concepts to the preschool children [39, 40].

Fig. 17. The teaching Assistant Robot in English Language and Peer Tutoring Robot [41].

Chandra, *et al.* in [42] developed an autonomous system for assisting children to improve their handwriting skills, as shown in Fig. 18. Their system entails using the social robot in one-to-one learning sessions with children. The mode of interaction between the child and the robot relies on the peer-tutoring approach in which the robot acts as a learner and the child acts as a teacher. The writing of the robot was generated by the algorithm incorporating the human-inspired movements and could reproduce a set of writing errors. Their results showed that the children learn with the robot which exhibits learning competency.

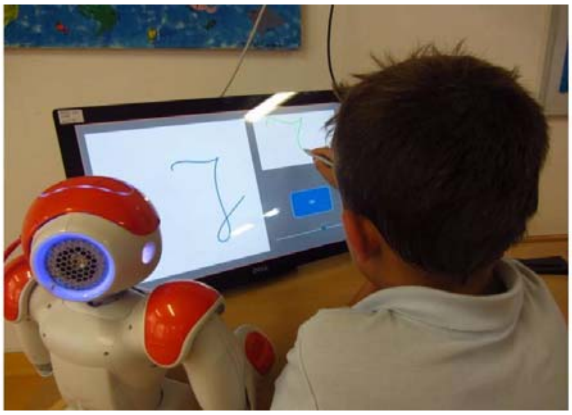

Fig. 18. A social robot for improving the handwriting skills of the children [42].

6. Other Applications

HRI can be found in other applications, which include service, home use, inventory management, and mining. In addition, Space exploration and UAVs are also some applications.

In home, the robot can help human in many tasks such as cleaning the floors and walls with sweeping and wet mopping functions, cleaning the windows and doors, preparing the foods in the kitchen, offering food and drinks to the guests, taking care with children, and so on.

The robot helps the human operator in mining industry as shown in Fig. 19 [43]. Using the robots increases the arsenal of the tools that help and support the miners to work in more safe and more efficient environment.

Fig. 19. The robot helps human in mining industry [43].

During the coronavirus outbreak, the robots are taking on a greater share of the work in some grocery stores starting from checking the shelves for low stock to helping in floor cleaning and moving inventory [44]. In Fig. 20 [44], the robot called "Pepper" is standing in front of the cash registers in the supermarket. The robot is informing the customers of the store about the rules of conduct in connection with the outbreak.

Fig. 20. The robot is informing the customers of the store about the rules of conduct in connection with the outbreak [44].

7. Discussion

In the previous sections, the applications of HRI in different areas in our real life are presented. For all these applications, highly efficient human-robot cooperation should be achieved. One of the main factors in HRI is safety, since the operator proximity to the robot can lead to potential injuries. Therefore, a system based on collision avoidance or detecting the collision should be found on the robotic system. Collision can be avoided by monitoring the environment using sensors as presented in [45-47]. Collision can be detected using model-based methods [48, 49] or using data-based methods [50-52].

Adapted controllers should also follow the human collaborator intention and the environment changes [53]. Therefore, this can lead to human-friendly robots and therefore the tasks can be performed easily and efficiently.

Searching for the best location of both the human operator and the robot can increase the speed of the co-manipulation task and the human operator comfort [10].

From this discussion, we can conclude that the methods for improving the HRI are very important and necessary for accomplishing the tasks and the applications easily and efficiently.

8. Conclusions

This manuscript has summarized some real applications of HRI. HRI could be found in industrial applications in picking and placing in the production lines, welding processes, assembling parts, and painting. Assistive robotics are one of the highest profile areas of HRI. For people with the physical and the mental disabilities, robots provide the opportunity for the interaction and the therapy. In addition, HRI could be commonly be widely applied in hospitals and nowadays HRI is very crucial for fighting against the new coronavirus (COVID-19). In agriculture, HRI helps with many tasks such as harvesting, seeding, fertilizing, spraying, hauling, weed detection, and mowing. HRI is effective and important in the field of education. The robot can help children in classrooms for different learning processes. HRI can also be found in other applications such as service, home use, inventory management, mining, space exploration, and UAVs. Methods for improving HRI are very important and necessary for accomplishing the tasks and the applications easily and efficiently.

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Cognitive and Learning-based Control: Applications in Robotics

Bin WEI

Algoma University, 1520 Queen St E, Sault Ste. Marie, ON P6A 2G4, Canada

Tel.: 705-949-2301, ext. 4270

E-mail: bin.wei@algomau.ca

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Abstract: In control arena, one of the most important issues is to effectively control the robot motion and force and in the meantime, the robots must safely respond to contact forces while interacting with people. Another issue is that how to handle uncertainties that are occurred during the process of interacting with environment. Human beings can control ourselves' motions (e.g. control arms to move, legs to move, whole body to move) perfectly. This partly attributes to the fact that human control system is based on millions of neurons that are receiving and sending signals to each other, and partly attributes to the fact that this control is formed by our initial learning. This paper reviews the most recent development on the brain and cognitive intelligence based control used in robotics. Some future research recommendations are proposed. It is concluded that the final goal is how to combine neuroscience, AI, and robotics so that we can make robots have more human-like performances.

Keywords: Adaptive control, Cognitive intelligence, Learning control, Robotics, Human-robot interaction.

1. Introduction

In 2000, the humanoid robot ASIMO is developed by Honda research group, and the robot can walk and climb stairs etc., but the robot cannot have physical interaction with humans [1-2]. Recently, the Boston Dynamics research group together with Google developed a humanoid robot Atlas, surprisingly it is not heavily based on artificial intelligence but motor control and learning through the state space model, and it is by far the most agile robot on the market [3-4]. However, the Atlas robot was not designed to have physical interaction with human beings, so it cannot really have physical interaction with human beings. Similarly, the recent developed humanoid robot Sophia that is largely based on artificial intelligence developed by Hanson Robotics research group can have verbal interactions with human beings, but not too much physical human robot interaction.

Before proceeding further, it is noted that biologically inspired robots have been developed in the past decades [5-9], in which researchers are trying to simulate and copy biology organisms to make robots more intelligent and accomplish complicated tasks. What about simulating and copying human behaviors (human nervous system) instead of animals behaviors? Since the most reliable and intelligent control system ever encountered is the human internal control system.

Human beings can control ourselves' motions (e.g. control arms to move, legs to move, whole body to move) perfectly. This partly attributes to the fact that human control system is based on millions of neurons that are receiving and sending signals to each other [10-12], and partly attributes to the fact that this control is formed by our initial learning [13-14]. It is noticed that when we were babies, we learned how to control the motions over and over again, and gradually formed the perfect control of movement.

Some of the traditional control systems (e.g. PD control) mimic the spring and damper system, as briefly illustrated in Fig. 1. Traditional control systems (used in robots) that are mainly geared to the industrial manufacturing purpose are no longer effective in human-robot interaction, e.g. one of the applications is eldercare. As serving an elderly people requires more complicated motions and safety issues need to be taken into consideration as well while the robot is interacting with elderly [15-18]. The robot requires more than just a position control, motion control, force control, or a trajectory planning [19-21]. It also involves with combination of above and unexpected motion control [22-24]. For example, in the process of assisting an elderly to walk around, if an elderly accidently falls, the robot needs to handle this unexpected motion and help to pick up the elderly.

A learning control system inspired by human brain and cognitive intelligence system seems to be a good candidate to address the above problem, i.e. how to design a human-nervous inspired learning control algorithm for assistive robots to help elderly people in their daily lives, for example, help to pour a cup of water and deliver it to the elderly, help to assist elderly to walk around, and help to clean the house. All these tasks need a robot and an advanced control algorithm. One of the most important issues is to effectively control the robot motion and force and in the meantime, the robots must safely respond to contact forces while serving an elderly people [25-27]. Another issue is how to handle uncertainties that are occurred during the process of, for example, serving an elderly people [28-30]. The development of physical assistive robots is not a main issue here, the main issue is to develop an advanced control algorithm to control the robots to execute an unexpected tasks in the process of assisting elderly people [31-33].

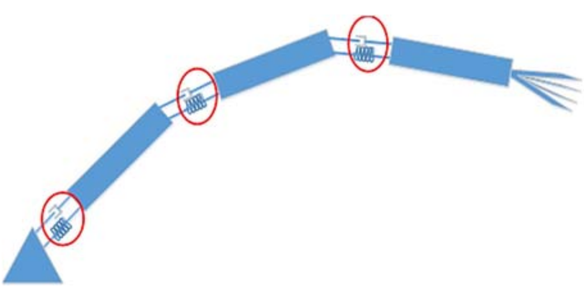

Fig. 1. PD control analogy.

Here, the most recent development of brain and cognitive intelligence based control are reviewed and the human-nervous-systems-based learning control algorithm for robots is discussed in order to further summarize and improve the methodologies in this field. This paper is essentially the extension of previous paper presented in the 1st IFSA Winter Conference on Automation, Robotics & Communications for Industry 4.0 (ARCI'2021) [34].

2. Cognitive Based Control in Robotics

In [35], the author studied how human beings control arms' movements by looking at the patterns of electrical activity in neurons when a person moves his or her arm through combining artificial intelligence and neuroscience, and then apply such skills to robots. The studies show that how artificial intelligence and neuroscience can help each other in order to advancing both fields.

Very similarly, artificial intelligence, computer programs, and brain organization are compared and investigated together in [36], and it came to the same conclusion that AI and brain organization are helpful to each other. The output of brain organization might be useful in better modelling and simulating of AI. In [37], a deep neural network is identified and trained by computational approaches in order to study the patterns of electrical activity of a monkey neurons in the process of recognizing an object. The deep neural network was modelled based on the human brain hierarchical architecture, and it is acknowledged that generally neural networks perform supervised learning. In [38], a "brain-like" control technique is used in the visual servo control of a redundant 7-DOF robotic manipulator for the tele-robotic operations application to remove the image-feature extraction and tracking requirements. However, the technique requires installation of advanced sensing systems and reconfigurable base. Furthermore, the force control is not considered and also safety issue is one of the major concerns when applying above approach. Precisely speaking, the above brain-like control technique can actually be considered as non-vector space control.

In [39-40], the intersection of computational neuroscience, cognitive science, and artificial intelligence are reviewed. It shows that by using Bayesian cognitive models, complex cognition will work in some cases, such as the way human minds model the real world by optimally combining previous experience. However, the study did not specify how we can apply such approach to robots.

In [41], a "learning nonlinear model predictive control" (MPC) policy is developed to minimize path-tracking errors by employing, for example, learning for the mobile robot path tracking problem. The robot is mainly used in the off-road terrain. The developed control policy employs a theoretically vehicle model and a disturbance model, and the authors modelled the external disturbances as a Gaussian process. The process is then further improved contingent on the experience that is collected during the earlier tests. However, the question of how to balance the covariance estimates provided by the Gaussian process model is still a challenge work. In [42], a new learning-based control structure, which makes the robot operate as a "social motivator" through providing assistance and motivation, is proposed for a socially-assistive robot that is able to make individuals involve in cognitively stimulating activities. The authors used a hierarchical reinforcement learning technique for the purpose of providing the robot to learn assistive behaviors based upon the activity structure. The result indicates that the developed learning-based control policy can effectively determine the best assistive behaviors of the robot, for example, over a game interaction.

In [43], the authors discussed how to build and make robots that learn like people. The article presented and illustrated two major challenges in the process of robot learning: image and character recognitions, and learning how to play a video game. The authors argued that the combination of neural network modeling and learning-based artificial intelligence could result in much better result and more human-like learning abilities than that of single artificial intelligence system. Furthermore, it also concludes that deep neural networks learning together with psychological ingredients could lead to a much higher level of cognitive control. The challenging problem and of course the next step of work seem to be that how to build the bridge between deep neural networks learning and psychological ingredients.

There are also numerous of recent studies focusing on the deep learning and neuroscience [45-51], but the studies did not specify how exactly to connect deep learning and neuroscience to robot controls.

In [52], a "recurrent emotional cerebellar model articulation controller neural network" is presented for vision-based mobile robots to handle complex nonlinearities in the dynamic equations so as to achieve accurate positioning tasks. The developed control neural network combines a recurrent loop with an emotional learning system and therefore generate a "cerebellar model articulation" control system, which is acted as the main piece of the control system module. The developed control system contains three parts: a sliding surface, the recurrent emotional "cerebellar model articulation controller", and a compensator controller, and the control system is designed based on the Lyapunov stability theory and therefore, the stability of the overall controller is guaranteed. However, the designed control network has certain limitations where the control network can only be used in target tracking due to the fact that lacking of self-organization mechanism in the overall control system. In [53], the authors proposed an approach by training machine learning regression algorithms to anticipate slippage related to individual wheels in mobile robots that are used in off-road conditions. The novelty about that study is that the machine learning regression is employed rather than classification to detect slippage and related uncertainties. The interesting part is that the slippage is considered as a random variable. The MIT single-wheel equipment is used as a demonstration, and the result shows that the Gaussian process regression leads to a trade-off among computation time and precision. Using deep learning approaches to model slippage as a discrete variable will be interesting to look at in the future.

In [54], a general structure of exploring the consciousness nature in cognitive robots has been developed, and the issue of how to create a humanoid robot that learns to conduct works based on imitation learning is discussed. It is pointed out that the above humanoid cognitive robot can be achieved by copying and following human-provided demonstrations (i.e. the so-called "learning from demonstrations") instead of pre-programming the robot. However, the potential issue is that the robot is very limited to generalize to a completely new set of circumstances where the robot needs to use different actions to execute the same intention, because the robotic system does not understand the demonstrator's intentions. In [55], the development of neuroscience inspired human–robot interaction is briefly reviewed, and some challenging issues are brought up. The study reviewed the above topic from the following two different perspectives: the development of social behaviour in robots, and human social perception. Nevertheless, it was concluded that we need to integrate different research areas to make significant progress in controls of human-robot interaction.

In [56], a framework for coordinating stimulus sport interaction scenarios with robots is developed based on motivational instruction patterns. It is shown that by employing a structured way of assessing multiple interaction configurations and robot platforms, one can obtain a deep understanding in psychological concepts that shape human-robot interaction. However, the study is still preliminary in terms of scenarios presented.

In the beginning of the century, people are looking at the adaptive control to handle the situation where parameters in the dynamic equation change with respect to time. Adaptive control still replies on models and it is a type of model-based control. Later, many research groups investigated the model-free control, particularly the deep reinforcement learning in robotics [57-68]. The challenging problem we are facing is that how to make robots deal with uncertainties and make corresponding decisions, and how to make robots truly achieve human-like intelligence.

In [69], the authors investigated the human–robot cooperative tasks by looking at the needed individual, based on affordance analysis and perspective-taking. The context is that robots and humans are put in a common space, and humans and robots exchange information mainly via verbal communication and social observation, and the robot is then anticipated to carry off interactive object manipulation by considering the human's intentions, skills and beliefs. The study presented is till preliminary. It does not consider cases where different beliefs might appear between the robot and human. Moreover, the study is only limited at the spatial and temporal situations, where a context selection consists of retrieving one monolithic set of beliefs rather than single one belief. In another interesting and similar study [69], a coordinated speech-based humanoid robot is developed that can follow human commands and produce poems, receive audiences feedback and thereafter display corresponding emotional responses, and produce body language movements accordingly.

The dialogue capabilities of the robot yet needs to be further improved in order to allow an active learning for extracting and organizing knowledge from human.

In programming arena, for example in Java, we have the concept of modularized programming [45], where one lengthy program is reduced to one main method and several blocks of sub-methods. Each of these sub-methods is one module, and each module does its own work and returns the result to the main method which utilizes the returned result. A Java example is shown here in Fig. 2 for the purpose of an illustration. Furthermore, it is argued that our human body does not only have one controller, but rather multiple controllers that are working together with the central nervous system, which is our brain and spinal cord. When humans control bodies, not all controllers are working at the same time. For example, when human humans grab an object, the only control system working might be the arm controller and other related controller, the controller that controls our facial expression might not be working. Or as another example, when human beings lay on the bed and relaxing, we still have all the controllers but most of the controllers are not performing to control any movement.

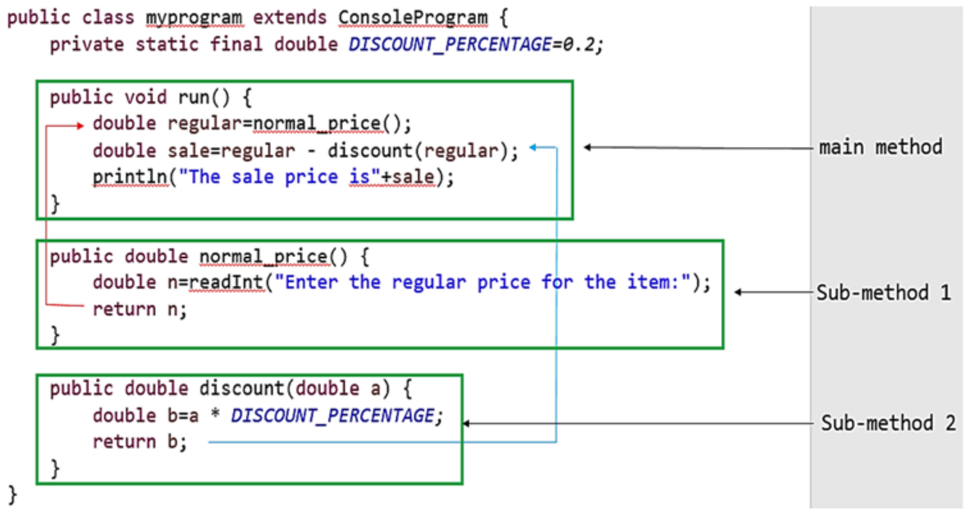

Fig. 2. A Java program example – modularized programming concept.

It is similar to the idea of under-actuated robotics [70-71], where the number of controllers is less than the number of joints, for example, in robotic manipulation. Many complicated robot motion, for example, robot walking, robot running, balancing an inverted pendulum, are achieved by under-actuated situation. Most of the robots in factory floors, e.g. assembly robots in car manufacturing, are fully actuated, where the number of the controllers equal to the number of the joints, and they can be achieved to have the adaptive control functions because of the fully actuated situation.

There are lots of control strategies currently, for example, optimal control [72-73], adaptive control [74-75], model predictive control (MPC) [76-77], etc. As a side note, the optimal control mainly focuses on how to control, for example, a robotic arm with minimum energy and quickest fashion. Adaptive control focuses on how to control, for example, a robotic arm with unknown dynamic parameters to make the robotic arm move as if the unknown parameters were known.

The idea of the multiple controllers working independent and together with the central control system might be one of the future research directions we can take to handle robot control in order for robots to accomplish more complex and delicate works, as conceptually demonstrated in Fig. 3. We can build a model to represent such hierarchy concept and apply such control to robots.

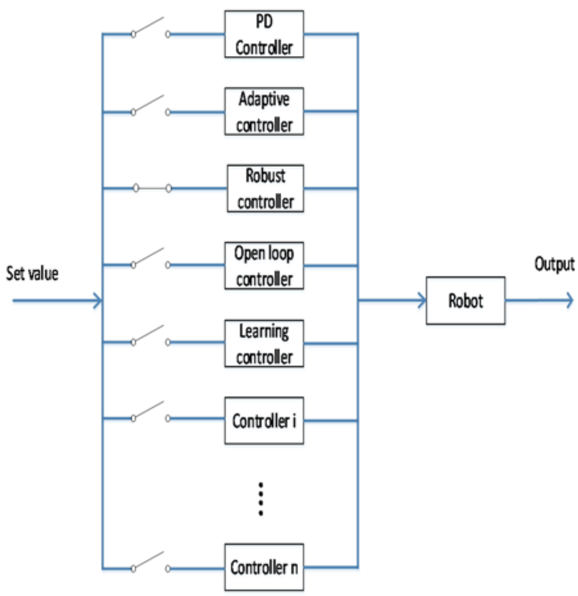

Fig. 3. Multiple controllers work together and independently to control a robot.

3. Discussion

The general approach as a future study that we are going to take for designing cognitive based control for robotics or human-nervous-system-based learning control algorithm is to build a mathematical model to resemble and represent human nervous system based on the structure and function of the nervous system, and then apply such model to robots.

As mentioned earlier, one of the main reasons that human can control and coordinate arms, legs, and whole body perfectly is that we have the initial learning. For example, if you are asked to write a sentence with your foot with a pen stuck in between the toes, you probably will have a very hard time to control such motion and write a sentence. This is because we did not have any initial learning on how to write a sentence with our feet instead of hands. Similarly, if you are asked to write a sentence with your left hand (if you are right hand side writer), you probably still will have a hard time to control such motion and write a sentence, again, the reason is that we did not have any initial learning on how to write a sentence with your opposite hand. But if you are trained or taught how to do that, and after practice over and over again, you then will have an easy time to control such unexpected motion as described above.

The following states how we are going to achieve human-nervous-system-based learning control algorithm in details: in the designing of such human-nervous-system-based learning control algorithm, the initial idea is to make the human-nervous-system-based learning control system have two major sections. The first section contains the learning control algorithm. A basic learning control concept is illustrated in Fig. 4.

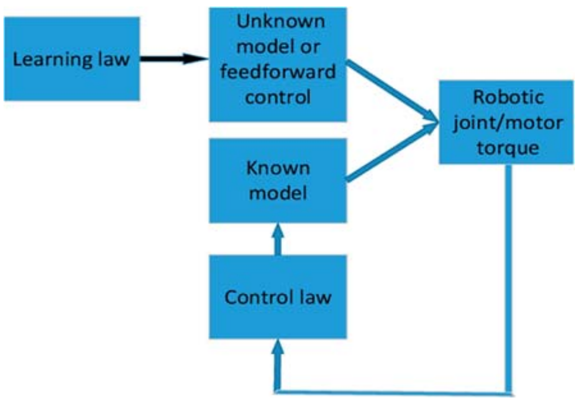

Fig 4. A learning control concept [59].

The learning control algorithm can be designed based on the artificial intelligence by simulating the human learning approach (learning over and over again) and modelling a deep neural nets model. After that, maybe we can add a block that is very similar to the structure of neurons that are receiving and sending signals to each other to the above learning control algorithm, and this forms the second section, which will be one of our future works. The purpose of the first section (the learning control algorithm) is to store enough "correct move" and "wrong move" information, it's very similar to initial learning, as described above. The purpose of the second section (the neurons alike structure) is to utilize the first section's information to communicate with the robot. Fig. 5 briefly illustrates the overall plan for designing a human-nervous-system-based learning control algorithm used, for example, in a socially assistive robot. The key problem that needs to be solved is the human-nervous inspired learning control algorithm instead of building a robot.

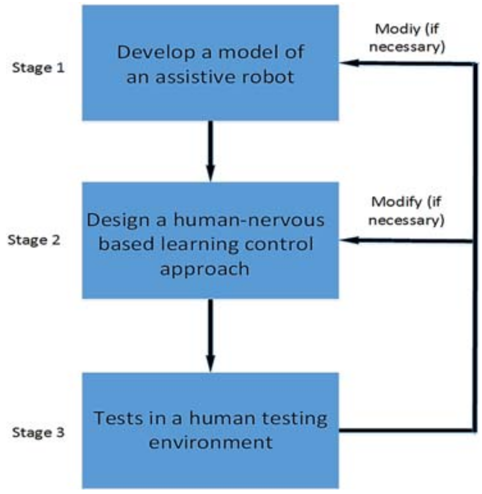

Fig. 5. Example of human-nervous inspired learning control algorithm design overall plan.

4. Potential Applications

Robotic systems have been used in many industrial areas, but its development in the human-robot interaction, for example, socially-assistive robots in eldercare, is still in the infant stage [79]. It is estimated that by 2030, there will be over 1 billion elderly people who are over 60 years old around the world. Young people will not be able to stay at home and serve their older parents often as they have to go to work. Thus the use of assistive robots in eldercare will become necessary in the near future. There are few robots being designed in the last decade where the robots can do some basic tasks for elderly, but mainly on the communication and entertainment level [80-82], not actually having physical interactions with elderly. The significance and potential impact of the cognitive based control research are summarized as follows:

1) By 2030, it is estimated that 20 % of world's population will be over 60 years old. The development of socially-assistive robots will greatly assist elderly people in their everyday lives;

2) The development of human-nervous inspired learning control algorithm will further push the development of the automatic control theory to a new

level and introduce a new concept of control, which can potentially be used also in advanced manufacturing. Manufacturing plays a crucial role in today's economy responsible for about 16 % of global gross domestic products. In current manufacturing industries (e.g. in manufacturing assembly lines), robots are working independently and not working with human operators. In order to improve the productivity and adapt to the rapid changes in production, current assembly robots are very limited in satisfying those needs. Whereas robots working with human operators is an effective approach to meet the needs of rapid changes in production.

5. Conclusions

The author here reviewed the most recent development of the brain and cognitive intelligence based control used in robotics in order to further summarize and improve the methodologies in this field. A human-nervous-systems-based learning control algorithm design framework for assistive robots is briefly illustrated and discussed. Some future research recommendations are proposed. It seems the final goal is that how to combine neuroscience, AI, and robotics so that we can make robots have more human-like performances.

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Data Quality: Enterprise Initiatives' Issues and WSN Challenges

[1, *] Ina Naydenova, [1, 2] Zlatinka Kovacheva and [3] Kalinka Kaloyanova
[1] Institute of Mathematics and Informatics, Bulgarian Academy of Sciences,
Acad. Georgi Bonchev Str., Block 8, 1113 Sofia, Bulgaria
[2] University of Mining and Geology, Sofia, Bulgaria
[3] Sofia University 'St. Kliment Ohridski', Faculty of Mathematics and Informatics
[1] Tel.: (+359 2) 979-38-28, fax: (+359 2) 971-36-49
E-mail: naydenova@gmail.com

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Abstract: This paper summarized the results of our previous work, outlining some important aspects of the data quality provisioning at the organizational level that are usually poorly understood or underestimated and therefore represent a significant setback in compiling a successful data improvement strategy. These aspects do not cover the specifics of the data quality issues in the field of sensor networks. In the current contribution, we examine the major challenges of providing high quality data collected by wireless sensor networks.

Keywords: Data quality, Sensor networks, Challenge, Context, Data quality initiatives, Decision-making.

1. Introduction

Nowadays data supports many enterprise level businesses, forming one of their most valuable assets. Its use can have short-term impact on the businesses but also medium or long-term implications. The way data is being currently used in data analysis to support decision making, including higher-level decisions such as operational (e.g. at a department, or local store level) or tactical (i.e., from the organization point-of-view) is a clear example of such implications. Thus, the need for organizations to possess high quality data is essential, as it can increase the opportunity for the organizations to deliver reliable services [1]. Data quality (DQ) is also a pre-condition for data analytics and Artificial Intelligence (AI) projects. Poor data quality can cause analytics and AI projects to take longer than expected (around 40 % longer), which means they will cost more or even they will eventually fail to achieve the desired results (70 % of AI projects). Therefore, if a company is looking to invest in AI, it must first develop, define, and implement an excellent data quality strategy [2].

The initiatives for provisioning of better data quality have their own features and specifics, in accordance with the different goals and levels of implication they are launched for. In [3], we have addressed several important aspects of enterprise initiatives to provide better data quality for tactical decision-making. In the current contribution, we will address the challenges of providing quality data collected by wireless sensor networks (WSN).

The rest of the paper is organized as follows. In Section 2, we summarize the results of our work given in [3]. We outline some common misunderstandings and underestimated aspects of the data quality provisioning at the organizational level that hinder the establishment of a successful strategy to improve data for the needs of decision making and business intelligence activities. These aspects do not cover the specific characteristics in providing quality data collected by sensor networks. They are focused mainly on issues related to the data quality initiatives' methodology, organization of work, attitude and maturity of the organizations to launch DQ programs, rather than specific technical challenges. Despite that, we believe that issues in discussion make sense for any DQ project, including the initiatives to provide better data for WSN applications. In our experience, a poor understanding of the addressed aspects is one of the main reasons for the failure or unsatisfactory implementation of the DQ initiatives, regardless of the company business activities. However, the WSN applications have their own specific challenges. Therefore, in Section 3, we take a closer look at the WSN-specific data quality issues. Finally, we make some conclusions in Section 4.

2. Misunderstood Aspects of Data Quality Initiatives

We can summarize the following key points that should be taken into account by the organizations looking to improve the quality of their data:

2.1. Contextual Nature of Data Quality

The concept that some data is good ("high quality") for some purposes but is poor ("low quality") for others is not always well assimilated. Incorrect data may have a different impact on the business, depending on the purposes for which the data is used. For example, if a wrong first customer name is registered in an IT system, this indicates the presence of poor data. However, for the task of mail notifications, where only the customer's last name is used, there is no quality issue with the system' data. At the same time, the wrong first name could be a problem if the person's identity needs to be verified. Poor data is often associated with the discrepancies between reality and the data stored in the system, but the quality of data is a much broader concept. Furthermore, data inaccuracies could be an issue for a given use case, but not interfere with others. A similar observation was shared back in 1990 in [4]. The perception that data quality should be defined in accordance with the consumer's needs is further developed in [5]. High quality data can refer to whether data meets the expectations of the users [6], which can be human users or systems, or can be defined as "data that is fit for use by data consumers" [5]. In the ISO/IEC 25012 standard [8] it is defined as "the degree to which a set of characteristics of data fulfills requirements". The authors of [5] also define a "data quality dimension" as a set of data quality attributes that represent a single aspect or construct of data quality. In subsequent studies scholars propose a variety of data quality dimensions. The majority of the authors include some versions of accuracy, completeness, consistency and timeliness among them [6]. It should be noted that quality dimensions give some structure to data quality expectations, but they have nothing to do with the task-dependent nature of the data quality. Let us take the completeness, for example: for the task of mail notification we need a complete and accurate mail address, but for the purposes of geographic segmentation only the city part of the address is required [7].

The contextual nature of the quality is a root of many challenges. The lack of understanding of the duality of data quality (true reflection of reality and dependence on the case of use) leads to a number of problems, such as inappropriate approach in setting data quality goals, difficulties in data quality issues assessment, incorrect expectations regarding the DQ provisioning processes and the business value to be achieved. It also raises the question of the usability of solutions that accumulate large amounts of data from various sources, without clear vision about their purposes of use.

2.2. Task-dependent Objective Measurement

How good is a company's data quality? Answering this question requires usable data quality metrics. Companies must deal with both the subjective perceptions of the individuals involved with the data, and the objective measurements based on the data set in question. Subjective data quality assessments reflect the needs and experiences of stakeholders: the collectors, custodians, and consumers of data products. It should be borne in mind that the objective assessments could be task-independent, but could be task-dependent too. Task-independent metrics reflect states of the data without the contextual knowledge of the application and can be applied to any data set, regardless of the tasks at hand, while the task-dependent metrics are developed in specific application contexts [9]. According to our observations, most of the business significant data quality problems in modern organizations require the use of task-dependent measurement. Also, there is a common expectation that objective data quality improvement necessarily implies business value. Unfortunately, the limited awareness of what data quality improvement can truly imply often drives technical approaches that do not always translate into improving the business. Objective data quality metrics (such as a number of invalid values or percentage of missing data elements) may not necessarily be tied to the business's performance [10].

Many publications discuss various assessment metrics and indicators. Different types of indicators are discussed as appropriate for different quality dimensions. However, guidelines and good practices of how to relate and adapt the objective metrics to the business context and consumer expectations are rarely discussed. This trend is particularly pronounced in publications related to quality assurance in the Big data area. Thereby the impression that the quality of data and its measurement is an objective one is reinforced.

2.3. The Importance of Data Quality Requirements analysis

Another common mistake is to underestimate the preliminary analysis to identify the extent of data quality issues and to draw up the quality improvement strategy. The allocated time and resources for the analysis phase usually are not enough. Many business professionals are not aware that they have to become part of such analysis, so they are not interested enough in the project aims. Other participants in turn focus on analyzing and profiling the data quality state in the databases, instead of interviewing the business users about the problems encountered by them. The organization remains unable to see the big picture of the quality issues' impact over its business and it is not able to decide how to achieve maximum benefit with minimum effort. The methodologies for data quality improvement also reflect in the underestimation of the need of a holistic analysis. Almost all methodologies include activities that examine data schemes and perform interviews to reach a complete understanding of data, but only a few of them consider the data quality requirements analysis step, identifying data quality issues from the business perspective and collecting new target quality levels [11].

2.4. Whose Responsibility is to Provide Quality Data?

One of the main factors for the success of data quality initiatives is to understand correctly, whose responsibility it is to provide quality data. In our experience, the misconception that data quality is mainly an IT problem and it could be solved by purchasing sophisticated (and often expensive) data quality tools is very common. One of the reasons for such a delusion is the assumption that developers bear primary responsibility for ensuring that the software they write works properly, no matter which data is fed into it. Since they write the code, they have the power to control how an application will respond when it receives low quality data. In the real world, even the best programmers cannot foresee every type of data quality issue that could occur within their applications. Even if they did, the applications might end up being overloaded by functions that handle obscure data quality issues [12]. Actually, the organization and its processes are always more important than the technology since they are defined according to company strategy [13]. The business professionals must not only be involved, but also lead the data quality initiatives. This is a consequence of the contextual nature of the quality. In fact, the businesses know the context and the indented uses of data better than anyone does.

Given the strategic importance that data plays in competitive markets, high data quality can only be achieved if IT and business find a mutually intelligible language, a mode of operation, that overcomes the traditional disconnect that can be observed in so many corporations. Conceptually what needs to happen to enable business alignment is bringing together problem holders and problem owners. The problem holder is the person who experiences "pain" from a problem; a problem owner is the person who controls the resources needed to resolve it. The problems resolutions lie in making the problem owner feel some of the problem holder's "pain" so he becomes motivated to do something about the problem [14].

2.5. Systems Interoperation in the Modern Business

The lack of overall vision for the data flows between information systems of the organization and the lack of effective strategy for synchronizing the changes in them often lead to the presence of inconsistent, obsolete and contradictory data. The managers rely on the corporate data warehouses as a "single source of truth". However, in modern data warehouses, which accumulate a huge amount of data from different operating systems, this is difficult to achieve in practice. Moreover, the operating systems that feed data warehouses are also used for an extraction of various reports. Correction of bad data must be done in all systems where copies are stored, although the data may be used for different purposes in different systems. Correcting them only in one system (as part of an initiative for data quality improvement in a particular application) will improve the quality of data locally, but will enlarge another severe problem – the existence of conflicting information at the organizational level.

2.6. Identical Objects Recognition

A severe problem in some organizations is the resolution of cases with duplication of data, especially when there are no clear criteria by which it is possible to identify two objects as identical (e.g. if some individuals do not have the same national identification number in different data sources). Similar problems are particularly relevant when collecting information from various sources and information channels in large data warehouses, data lakes and Big data solutions. Duplicate information is a major source of inconsistency and lack of integrity in the organization's data. It is often associated with increased risks of submitting inaccurate information to external partners and regulatory authorities. The data integrity issues contribute greatly to the loss of trust in the organization's data, both by the company's employees and by customers, contractors and external partners, which in turn leads to a loss of reputation.

Ignoring or postponing the resolution of problems with duplicate objects is a common situation. To resolve such problems on a company level, organizations are looking for master data management solutions. Providing master data management across the enterprise is a complex task that requires investment of significant funds, allocation of a lot of human resources, amendments in already established and verified business processes, etc. However, the issues with duplicate objects can be solved (or at least minimized to a satisfactory level) with lightweight approaches. For example, efficient deduplication of objects can be achieved by using record linking techniques. In [3] and [15] we are sharing details of our implementation of a method for individuals and legal entities unification, which has been used productively for more than 15 years.

3. Challenges in Providing the Quality of Data Collected by WSNs

3.1. Quality of Data in Sensor Networks

With the emergence of the Internet of Things (IoT) and WSNs, sensor devices are deployed across the globe in a variety of fields such as healthcare, industry, agriculture, home, transport, etc. An IoT application may have hundreds or thousands of sensors, which produces vast amounts of data, but the data is useless if it is riddled with errors, as poor sensor data quality caused by the errors may lead to wrong decision-making results [16]. Ensuring the quality of monitoring data is fundamental to avoid false alarms or ignoring relevant data. However, because the sensors are located in the physical environment, they are constantly being subjected to factors that directly interfere with the data quality [17]. The hostile environment in which sensors are deployed plays a big part in the quality of the transmitted data [16]. For example, sensors for temperature, light, or humidity measurements are often placed outdoors and are subjected to potentially strong currents, debris accumulation and tough weather conditions, which might affect the operation of the sensors. Many errors in wireless sensor networks also occur due to characteristics, such as low-cost sensors, limited resources, and link variation. These errors appear in different modes, for example, the data loss or anomalies caused by hardware, the data failure due to transmission delays, and the sampling jitter caused by the node task conflicts. The dataset collected by the sink node (base station) may simultaneously result in all of these errors [18]. However, the WSN data could be incorrect not only due to a faulty sensor or corrupted communication. The erroneous data coming from sensors can be identified in two major categories: intentional or unintentional errors. Intentional data errors can be caused by physical or logical attacks over sensors (i.e. malicious attacks) and unintentional data errors are generally caused by hardware malfunction (or stochastic errors), misplacement (conditional errors) or exhausted resources (systematic errors) [19]. Consequently, there is a trust issue related to the collected data, which demands an extensive human intervention in terms of time and knowledge specialization, data validation tasks and periodic maintenance of sensors. To deal with this problem, it is necessary that the quality of collected data be continuously and automatically validated [17]. Simple strategies to overcome data quality problems, such as using industry grade sensors, which are more accurate, stable and robust, are not feasible for applications that require the deployment of large and dense sensors networks, which is the case for many IoT applications [16]. This approach will minimize a vast range of data errors, but it is far from solving all data quality issues and therefore it will not eliminate the problem with the lack of trust and the need of constant data validation. In addition, having to deploy many highly accurate but expensive sensors will incur higher deployment costs. It is therefore not surprising that in recent years automated software solutions to eliminate errors in data at the lowest possible architectural level have been actively developed. Intelligent sensors, self-calibrating and self-organizing protocols are emerging, which is an important necessity, especially if the WSN has to be located in hard-to-reach places.

In essence, data quality issues can be faced taking two main perspectives: (a) by deploying dependability techniques to mask faults and enforce the reliability of the system or (b) by enhancing the system with means to continuously assess and characterize the quality of data. In the first case, the system will not be aware of the quality of data, and hence, if a certain quality is needed, it must be enforced by design, confining the effects of faults a priori. Considering sensors to be the main source of data, errors in sensing measurements are handled by procedures that are established based on a deep understanding of the characteristics of the sensors. Missing readings may be handled by oversampling, and glitches, like outliers and noise, can be masked by averaging. In the second case, given that the system can be aware of the quality of data at run-time, it is better suited to be used in environments where full knowledge of the operational conditions is not known in advance. In this case, mitigation techniques must be deployed to handle faults and data quality problems at run-time, for instance exploiting application semantics to determine appropriate data corrections and to regain the needed data quality. Given that no system can be built to exhibit 100 % reliability, the two perspectives can be combined [17].

3.2. WSN Challenging Aspects

Many of the challenges in providing quality data collected from sensor networks are related to the following factors:

3.2.1. Environmental Conditions and Vandalism

As we mention above, the WSNs operations of sensor nodes are frequently susceptible to environmental effects. Wireless sensor networks allow surveillance of large areas that are remote, difficult to access, and/or dangerous to humans. Sensor devices are generally defenseless from outside physical threats, both from humans and from animals. Such acts often result in rendering sensors dysfunctional, which definitely affect the quality of produced data ([17], [20]). To monitor some phenomenon, sensors may be deployed in environments with extreme conditions (e.g. a mountain's summit). In such conditions, sensors may become dysfunctional or unstable due to many events (e.g. snow accumulation, dirt accumulation, etc.). Furthermore, the maintenance of such sensors is rarely ensured considering the inaccessibility of terrains [17]. In these scenarios, it is possible for multiple nodes to fail at the same time and partition the WSN into disjoint segments. Such loss of connectivity may cause service disruptions and render the WSN useless. Given the critical role a WSN plays and the fact that deployment of additional nodes may be infeasible, the WSN must have the ability to self-heal and restore connectivity by utilizing surviving resources [21]. Restoring network connectivity in a distributed, localized, efficient and intelligent on-demand manner is one of the major challenges in designing wireless sensor networks.

3.2.2. Low Cost Sensor Devices, Hardware and Resource Constraints

The things in the IoT suffer generally from a severe lack of resources (e.g. power, storage, etc.). Their computational and storage capabilities do not allow complex operations support. Furthermore, they are usually battery-powered and they often operate with discharged batteries [17]. Power is considered the most critical limitation among others as sensing and processing must be accomplished within a limited period of time. Computational and storage capabilities do not allow complex operations due, in turn, to the battery-power constraints among others. Resource management systems depend mostly on process migration by distributing the tasks among nodes [22]. For better network applicability, the nodes in the sensor networks are usually heterogeneous: they have different energies, functions, communication abilities, and so on. Some nodes in the network are endowed with stronger ability to enhance the network communication, which are called "super nodes" [23]. However, the ordinary sensors may lack precision or suffer from loss of calibration or even low accuracy, especially when they are of low cost. Faulty sensors may also result in inconsistencies in data sensing. A sensor node fails, but it keeps up reporting readings, which are erroneous. It is a common problem for sensor networks and an important source of outlier readings. Considering the scarce resources, data collection policies are adopted, which usually make trade-offs that affect the quality and cleanliness of data [17]. Since most traditional cleaning techniques have paid limited attention to reasonable availability of computational resources, a challenge for providing high data quality in WSNs is how to minimize the energy consumption while using a reasonable amount of memory for storage and computational tasks [24].

3.2.3. The Huge Volumes of Data and Architectural Complexity

While IoT sensors and devices collect tons of valuable insights, they also generate massive, high-speed data streams. As a point of reference, IoT devices and sensors can capture gigabytes of data within a few hours [25]. The huge volumes pose a number of challenges to the efficient transmission and processing of data, including in terms of methods and algorithms for quality assessment and data cleaning. The large number of devices in the sensor networks not only increases the amount of data, but also accumulates the chance of error occurrence. In addition, considerable amounts of sensed data are of no interest, meaningless, and redundant [26]. In such circumstance, it can be difficult to spot truly meaningful patterns. Therefore, a challenging aspect in sensory data processing is the need of a mechanism for extracting meaningful information from redundant data and providing a consistent, accurate and reliable data set in an efficient manner.

The management of the rapidly growing volumes is also a challenging task. As IoT adoption continues to rise, organizations from every sector struggle to keep up with these massive datasets expanding at exponential rates. This requires a robust architecture for efficient storage and retrieval of data. A high-level view of a typical IoT architecture includes three conceptual layers: Acquisition or Perception layer (measures and collects readings via sensor devices), Network layer (determines routes and transmits readings using wireless technologies such as WiFi, 2G/3G/4G, Bluetooth, LoRa, etc.), and Application layer. Typically, the Application layer is designed and implemented using Big data architectures such as Apache Hadoop, Spark, or Kafka. Virtually every layer has its own architectural challenges. The added complexity of the architecture causes new errors to be potentially introduced in each layer. Unlike typical wireless networks, WSNs have serious deficiencies in terms of data reliability and communication owing to the limited capabilities of the nodes. In the Network Layer, poor data quality arises from congested and unstable wireless communication links in sensor networks, which causes data loss and corruption. Omission, crash and delay faults as well as message corruption are the most common network errors that lead to DQ issues (data integrity issues, missing data, inaccurate data etc.) [27]. Design of a sensor network includes the hardware constraints, power constraints, operating environment, network architecture, routing topology etc. Finding a trade-off between the desired functionality and the available limitations when designing the network is a challenging task, but the expected accuracy of information is an important factor that is always considered [28]. In the Acquisition layer, damage to sensor devices or battery depletion are the cause of most data errors [16]. Typical sources of unreliable data at this architectural level are the so-called "soft faults" such as constant offset errors, drifts, stuck-at-zero errors, trimming errors, noises and outliers [16].

3.2.4. Data Redundancy

In Wireless Sensor Network (WSNs), nodes are densely deployed in a region to collect information. Sensors sense the similar data and forward to sink. This similar data sometimes leads to redundancy at the sink. The redundant data results in more accuracy, reliability and security whereas elimination helps in energy saving as most of the energy of a sink node gets wasted in dealing with the redundant data. Redundancy exploits to improve various data quality factors such as [29]:

• *Reliability*: Redundancy ensures the reliability in WSN. Redundant data produced by the sensors ensure more accurate data as compared by the single entry data. Sometimes sensor devices are providing imprecise measurements due to environment conditions. For this reason, reading from a single sensor may not provide reliable data. The reliability of the system could be enhanced by employing redundant data from the same sensor nodes or from other sensor nodes.

• *Accuracy*: If two or more independent sources collect the same piece of data over a period of time, these pieces can increase the associated confidence and provide accurate data.

• *Consistency*: Different data values bring conflicting information, this conflicting information is reduced by using spatial redundancy, temporal redundancy and information redundancy.

• *Detect malfunctioning or find out malicious nodes*: Analytical redundancy is used to detect malfunctioning or malicious sensors. This process uses a mathematical model in which past and present values of neighbor sensor nodes are used to predict the value of a sensor. This predicted value is then compared with real sensor value to find malicious sensors.

• *Completeness*: The redundancy allows implementation of techniques for online reconstruction of missing data.

Elimination of redundant data improves the lifetime of a sensor network whereas incorporation of redundancy enhances data quality. Data fusion or aggregation techniques used to deal with redundancy either drop the redundant data or use redundant data. The establishment of a mechanism that achieves both, i.e. reliable data as well as energy savings through utilizing redundancy is another challenging aspect in WSN [29].

3.2.5. Real-time Data Streaming

The need of real-time data processing in many sensor network applications presents a number of challenges. Some challenges are inherent to the nature of data streams, and the quality evaluation algorithm has to face these constraints. Classical cleaning and evaluation algorithm, which is designed to process static data, should be modified to face the real-time processing specifics. For example, in the case of real-time processing, data values arrive at a different rate, so the evaluation algorithm should provide a mechanism for processing existing data before the arrival of the new incoming data. Transient data is also a significant challenge. Data expires after a while and loses credibility, so data processing should be done before it expires. In addition, data distribution may change after some time, and if the evaluation algorithm fails to find the new distribution, it will not be adequately performed [30].

The machine learning algorithms have their special challenges in terms of real-time processing. For specificity, we will give some examples. Data preparation is an essential part of a machine learning solution. Real-world problems require transformations to raw data, preprocessing steps and usually a further selection of 'relevant' data before it can be used to build machine-learning models. Trivial preprocessing, such as normalizing a feature, can be complicated in a streaming setting. The main reason is that statistics about the data are unknown a priori, e.g., the minimum and maximum values a given feature can exhibit [31]. In most clustering algorithms, the number of clusters is one of the crucial parameters to be defined. Since there is no access to all data in the data stream, it is impossible to specify the number of clusters. Not specifying the number of clusters leads to the production of arbitrary shapes, and ultimately it will be difficult to analyze these clusters [30]. In the case of batch processing, the classification algorithms could produce a model with reasonable accuracy, which is trained and tested over a selected set of data, but in the streaming data, specifying the size of test data and updating the model are major challenges. Due to the challenging aspects of real-time data processing, so-called hybrid approaches have recently gained popularity. These approaches work both on batch and stream data, typically using static data to build a model and apply the model to the data stream.

It should be kept in mind that each particular business and even task may require a completely different approach to real-time analysis. Choosing the data collection and transmission interval that is right for the specific task purposes may also be challenging. Choosing the right interval so that it is not too frequent but allows valuable insights to be extracted in time is specific to every enterprise [32].

3.2.6. Data Security

WSNs and sensor nodes can be subject to attacks that may significantly affect the quality of sensor data, among other consequences for the application. Because the IoT delivers access to enterprise IT resources beyond an organization's protective firewalls, connected devices are often targeted by hackers. Endpoint devices in the IoT are vulnerable for many reasons. Since they are in external settings, endpoint devices do not have the same traditional perimeter security protection as centralized resources. IoT devices are designed to be small and lightweight in order to quickly emit data and they have the necessary hardware and processing power of infrastructure with more robust security (e.g. no support for cryptographic operations because of their high consumption of resources) [33]. In addition, it is difficult always to authenticate the devices in a network. These, as well as some other factors, lead to increased risks of attacks to alter data transmitted by a sensor device that can lead not only to wrong decisions, but also to triggering malicious actions or events (both by humans and by machines).

3.2.7. Establishing a Connection Between Errors in Data and Their Causes

The errors in WSN data can be classified in two basic categories: systematic errors and random errors. Generally speaking, the systematic errors could be compensated by self-tuning and self-calibration processes, while random errors should be removed or replaced by predicted values using anomaly detection techniques. However, data errors can have many different forms and causes. For example, errors that randomly occur in the data may be associated with a systematic cause (e.g. dust accumulated in the sensing unit). Establishing a link between errors and their causes is a challenging task. By having this link, the errors can be tolerated at their source [34].

This is one reason some of the anomaly detection methods to carry out further analysis to determine whether a real anomaly has been detected or it is a result of an event affecting certain segments of the network (e.g. a fire in a forest, a gas leakage in a coalmine, a flood in an agriculture field etc.). Virtually, the ability to determine the causes of data anomalies is a key point in selecting adequate error handling actions – automatic correction or error ignoring, triggering an alarm, notification of force majeure event, etc.

3.2.8. Self-calibration Complexity

The calibration procedures in uncontrolled environments could be a complex task. The sensor nodes are exposed to environmental noise and hardware failures, and the mismatch between factory calibration conditions and in-field conditions makes the calibration of sensors challenging. Moreover, different sensors require different calibration procedures, and the reference values might not be readily available. Therefore, in general, even when the response function is known, calibration in uncontrolled environments is difficult. An example is an ozone (O_3) sensor whose output value depends not only on the O_3 concentrations but also on the environmental conditions – temperature and relative humidity – of the place in which the sensor is deployed. Conducting a multiple linear regression with respect to ground-truth O_3 concentrations in a place with different environmental conditions than those of the place in which the sensor node will be deployed can produce large errors in the predicted O_3 concentrations [35]. The temperature sensors have a similar behavior – on-site calibrated sensors behave differently when placed in another location because of the difference in environmental conditions between the two locations (solar radiation, humidity, wind speed, rainfall, azimuth, etc.) [36].

3.3. In Summary

Sensor data comes very often with a variety of quality issues, posing many challenges. This can occur due to diverse reasons including power outages at sensors, network issues, sensor malfunctioning or external influences. Sensor data recovery is a great challenge due to the spatio-temporal nature and their stochastic distribution. Re-transmitting the data cannot be a meaningful solution in the context of IoT Analytics as most of the IoT applications operate in real-time data streams, which would mean that the delayed data is considered useless. Besides that, the computation and energy cost limit the sensor's efficiency as these devices are usually constrained in terms of battery, memory, and computational resources. High-quality data input is imperative to empower to make quick data-driven decisions. Poor data including inaccurate, non-consistent, missing or incomplete data leads to inconvenient, time-consuming and expensive failures [37]. Although common types of errors produced by sensor networks have been well studied and a number of good solutions have been found to eliminate them, the issues with the completeness, accuracy, consistency and timeliness of data cannot be solved completely. Therefore, organizations working with WSN applications must identify the data quality issues and ensure the quality of sensor data streams in accordance with their goals and requirements. It is prudent that the established methodologies and proven practices be followed in providing quality data. Unfortunately, it is currently difficult to find DQ methodologies that are tailored to sensor networks. Numerous articles address individual aspects of providing quality data collected by sensor networks, but comprehensive DQ management methodologies are missing. In fact, we found only one examination of such methodology in [27]. However, we expect new studies in this area to appear in the near future.

4. Conclusions

Data quality has been a topic of interest to the scientific community for more than 30 years.

Accumulated knowledge and experience are significant, but there is still much to be done. The recent surveys show that companies are failing in their efforts to become data-driven. At present, many CEOs understand in principle the value and potential that data offers yet seem reticent to fully trust what the data tells them. KPMG International's recent Guardians of Trust study highlighted the extent of this conflict — just 35 percent of executives surveyed said they had a high level of trust in their own organization's use of data analytics while 25 percent admitted they either have limited levels of trust in, or actively distrust, the data they receive. In addition, 67 percent of CEOs say they have ignored the insights provided by data analysis or computer-driven models in recent years, because they have contradicted their own intuition or experience [38]. It is probably not a surprise, then, that 36 percent of CEOs admit they cannot make data-driven decisions until they invest significantly in data quality [39].

Our experience shows that when it comes to enterprise DQ initiatives most organizations have the same class of problems and obstacles to achieving better data quality. Many issues are a consequence of underestimating the importance of the business context and the domain knowledge, precise specification of the data use purposes and an active involvement of the domain experts. It is widely expected that IT and data science professionals are the people in charge of high-quality data providing, but in terms of data-driven decision-making, this is not a reasonable expectation. As far as the IoT and WSNs are concerned, the technical challenges that are in the hands of engineers and data science professionals are far more than in DQ provisioning for tactical business decisions. This is partly because the data quality issues in the sensor networks are focused on particular data uses. In general, the WSNs data are collected in a specific context for specific data uses and the professionals are looking for effective methods to clean up in this context. Therefore, it is not surprising that the discussed data quality issues in the field of IoT and WSNs have their unique challenging aspects, which are different from the challenges in data warehousing and strategic decisions. However, some data quality issues are in common. For instance, any DQ initiative, regardless of its type or context, must meet the needs of data consumers in order to define an effective data improvement strategy; the data quality metric, assessment and cleaning algorithms should be adapted to the business/domain context; the domain experts should be actively involved in the DQ initiative and requirements definition, etc.

In the current article, we have paid attention to only a few data quality issues and WSN challenges, which we consider as important enough to be addressed, but their list is much longer for open discussion. In our opinion, the efforts in the data quality area should be focused not only on the development of new techniques and methodologies, but also on the promotion of common mistakes, as well as the sharing of good practices.

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Periodic Solutions to a Modified Elman Neural Network

[1, *] Zlatinka KOVACHEVA and [2] Valéry COVACHEV
[1] Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia 1113, Bulgaria
and University of Mining and Geology, Sofia, Bulgaria
[2] Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia 1113, Bulgaria
[1] Tel.: +359885018822
E-mail: zkovacheva@hotmail.com

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Abstract: Elman neural network is a recurrent neural network. Compared with traditional neural networks, an Elman neural network has additional inputs from the hidden layer, which form a new layer called the context layer. The standard back-propagation algorithm used in Elman neural networks is called back-propagation algorithm. Elman neural networks can be applied to solve prediction problems of discrete-time sequences. In the present paper, for a modified Elman neural network with a periodic input, we present sufficient conditions for the existence of a periodic output by using Mawhin's continuation theorem of the coincidence degree theory. Examples are given of Elman neural networks satisfying these sufficient conditions. Periodic solutions are found for particular choices of the weights, self-feedback factor and periodic inputs. Further on, sufficient conditions are presented for the global asymptotic stability of a periodic output. The periodic outputs corresponding to the solutions previously found are shown to be globally asymptotically stable for any continuous transfer functions of the output layer.

Keywords: Elman neural network, Hidden layer, Context layer, Periodic input and output, Mawhin's continuation theorem, Global asymptotic stability.

1. Introduction

Artificial neural networks are computational paradigms which implement simplified models of their biological counterparts, biological neural networks. Biological neural networks are the local assemblages of neurons and their dendritic connections that form the human brain. Neural networks process information in a similar way the human brain does. The network is composed of a large number of highly interconnected processing elements (neurons) working in parallel to solve a specific problem. Neural networks learn by example.

An important application of neural networks is pattern recognition. Pattern recognition can be implemented by using a feed-forward neural network that has been trained accordingly. During training, the network is trained to associate outputs with input patterns. When the network is used, it identifies the input pattern and tries to output the associated output pattern. The power of neural networks comes to life when a pattern that has no output associated with it, is given as an input. In this case, the network gives the output that corresponds to a taught input pattern that is least different from the given pattern.

Elman neural network [1] is a kind of recurrent neural networks. Compared with traditional neural networks, an Elman neural network has additional inputs from the hidden layer, which form a new layer called the context layer. So the standard back-propagation algorithm used in Elman neural networks is called Elman back-propagation algorithm. Below we give a brief overview of the literature on applications of Elman neural networks.

In [2], an overview of the structure and learning algorithm of the Elman neural network is presented. A modified Elman network is proposed by adding new adjustable weights that connect the context nodes with output nodes. Convergence speeds of the two network structures are compared. Theoretical analysis and simulation results show that the improved neural network-based identification method has the advantage of identifying both linear and nonlinear dynamic systems.

In [3], an overview of the structure of the Elman neural network and its modified form is presented. By comparing with the discrete PID (Proportional, Integral, and Derivative) control algorithm, their dynamic characteristics are fully discussed using the z-transform function. It is concluded that the modified Elman network has better dynamic properties.

With the rapid development of internet, the security of internet becomes a vital problem. In order to prevent hacks from intruding internet systems, intrusion detection becomes one of the “hottest” subjects. Intrusion detection systems detect and prohibit abnormal actions. By building profiles of authorized computer users, the neural network can be trained to classify the incoming computer traffic into authorized traffic or not authorized traffic. A hybrid RBF/Elman neural network model that can be employed for both anomaly detection and misuse detection, is presented in [4]. The intrusion detection systems using the hybrid neural network can detect temporally dispersed and collaborative attacks effectively because of its memory of past events. The RBF (radial basis function) network is employed as a real-time pattern classification and the Elman network is employed to restore the memory of past events.

Elman neural networks can be applied to solve prediction problems of discrete-time sequences [5-8]. In [6], a novel prediction algorithm based on an improved Elman neural network ensemble for quality prediction is proposed, thus achieving the quality control of designed products at the product design stage. First, the Elman neural network parameters are optimized using the grasshopper optimization method, and then the weighted average method is improved to combine the outputs of the individual neural networks, where the weights are determined by the training errors. Simulations are conducted to compare the proposed method with other neural network methods and evaluate its performance. The results demonstrate that the proposed algorithm for quality prediction achieves better accuracy than other neural-network methods.

Two improved Elman network models, output-input feedback and output-hidden feedback, are proposed in [7] based on the modified Elman network. A recurrent back-propagation control network model is developed by using the output-input feedback Elman network as a passageway of the error back-propagation. The stability of the improved Elman and recurrent back-propagation control networks is analyzed. Adaptive learning rates are given in the form of discrete-type Lyapunov stability theory, which can guarantee the convergence of the improved Elman and recurrent back-propagation control networks. The speed of the ultrasonic motor is identified using the modified Elman network, output-input feedback and output-hidden feedback Elman networks, respectively, and some useful comparable results are presented. Numerical results show that the recurrent back-propagation controller is effective for various kinds of reference speeds of the ultrasonic motor and the proposed scheme is fairly robust against random disturbance to the control variable.

In [8], an Output-Hidden Feedback Elman Adaptive Boosting-Bootstrap Aggregating algorithm is proposed under a comprehensive diagnosis framework. First, the original signal is decomposed, denoised and reconstructed by Ensemble Empirical Mode Decomposition. Then, an output-hidden feedback Elman neural network is designed by increasing a feedback from the output layer to the hidden layer based on Elman neural network. This improves the memory function for dynamic data of rolling bearings. Furthermore, for achieving diagnostic accuracy and algorithm stability, Output-Hidden Feedback Elman AdaBoost-Bagging algorithm is developed as a strong learner through the dual integration of AdaBoost algorithm and Bagging algorithm. Experimental results show that the proposed algorithm not only has a good diagnostic performance on different stages of rolling-bearing faults, but also achieves higher generalization ability and stability. This multi-stage fault-diagnosis framework provides a novel tool and an effective solution for rolling-bearing fault diagnosis.

The Elman neural network is one of the most widely used and most effective neural-network models in artificial neural networks and has powerful processing ability for nonlinear decisions [9-10]. The paper [9] proposes a method of seam-tracking monitoring during high-power fiber laser welding. A visual sensor system is employed to capture the infrared images of molten pools and the surroundings in the laser welding process. A weld-seam position variable is extracted by the image difference and centroid algorithms. The state and measurement equations for weld seam position are established based on an eigenvector derived from the weld-seam position variable. A Sage-Husa adaptive Kalman filter, as an estimator of the noise statistical characteristics, is applied in order to enhance the filtering precision. By embedding an Elman neural network into the adaptive Kalman filter, an error estimator is used to compensate for the filtering errors. The results of the welding experiments have demonstrated the effectiveness of the proposed method to improve the accuracy of weld detection.

The paper [11] presents an improved Elman neural network-based algorithm for optimal wind-energy control with maximum power point tracking. An online training improved Elman neural-network controller using back-propagation learning algorithm with modified particle swarm optimization is designed to allow the pitch adjustment for power regulation. The node connecting weights of the improved Elman neural network are trained online by back-propagation methodology. Modified particle swarm optimization is adopted to adjust the learning rates in the back-propagation process to improve the learning capability. The performance of the proposed Elman neural network with modified particle swarm optimization is verified by many experimental results.

The Elman neural network can be considered as a special kind of feed-forward neural network with additional memory neurons and local feedback. Because of its better learning efficiency, approximation ability, and memory ability than other neural networks, the Elman neural network can not only be used in time series prediction, but also in system identification and prediction [12-13, 8, 14].

In [12], the weights, thresholds and numbers of hidden-layer neurons of Elman networks are optimized by a genetic algorithm. It improves training speed and generalization ability of Elman neural networks to get the optimal algorithm model.

According to the requirement of real-time monitoring of the conversion rate of vinyl chloride in the production process of polyvinyl-chloride polymerization and the nonlinearity of the industrial data, in [13] an Elman neural network with strong nonlinear performance is chosen to build the soft-sensor model. So the whale optimization algorithm is adopted to optimize the Elman neural network, to avoid it falling into a local optimum. At the same time, to solve the problem that the position of the search agent is randomly distributed in the initialization process of the whale optimization algorithm, and to introduce the idea of chaos, a chaos whale optimization algorithm based on the idea of chaos is proposed to improve the diversity of all search agents and egocentricity of agent search by utilizing the chaotic features.

In [14], a data-driven prediction method combining condition-monitoring data and Elman neural network is proposed. This method finds the remaining useful life of ultrasonic motor by predicting the tendency of motor-performance degradation index. First, the improved particle optimization algorithm is employed to enhance the prediction accuracy of Elman neural network. Principal component analysis is used to extract the motor-degradation index from condition-monitoring data. Then Elman neural network prediction model is established to predict the variation trend of the degradation index, and the motor failure threshold is applied to evaluate the value of motor remaining useful life. Finally, the proposed model is used to perform the prediction test on three PMR60 ultrasonic motors and compare with three benchmark models. Experimental results indicate that the proposed method is a new effective method for estimating the remaining useful life of ultrasonic motor.

In order to improve the load-forecast precision and availability of power system, a method based on Elman neural network and MATLAB is presented in [15] to create a load-forecast model. Using actual load data to train the model, the emulation results show that the model has fast convergence speed and high forecasting precision, which can meet the needs of running and scheduling in power system, and using neural network tool-box in MATLAB to program can make the worker free of elaborate program and make the working efficiency improved effectively. An example shows that the method is feasible and effective.

In [16], an Elman neural network with a weather component is proposed for the power-load forecasting. Elman neural network can meet nonlinear recognition and process prediction of the dynamic system, and make power system have the ability to adapt to time-varying characteristics in mechanism. It is proved by simulation results that this model has a good performance in increasing forecasting accuracy because of its inherent dynamic behaviour and memory behaviour. The forecasting ability of Elman neural network is better than of back-propagation neural-network dynamic system, and has better adaptability to dynamic forecasting and prediction problem in mechanisms.

In [17], a novel modified Elman neural network-controlled permanent-magnet synchronous generator (PMSG) system, which is directly driven by a permanent-magnet synchronous motor (PMSM) based on wind turbine emulator, is proposed to control the output of rectifier (AC/DC power converter) and inverter (DC/AC power converter). First, a closed-loop PMSM drive control based on wind-turbine emulator is designed to generate power for the PMSG system according to different wind speeds. Then, the rotor speed of the PMSG, the voltage, and current of the power converter are detected simultaneously to yield better power output of the converter. Since the PMSG system is a nonlinear and time-varying system, two sets of online trained modified Elman neural-network controllers are developed for the tracking controllers of DC bus power and AC power to improve output performance of rectifier and inverter.

Because of the chaotic nature and intrinsic complexity of wind speed, it is difficult to describe the moving tendency of wind speed and accurately forecast it. In [18], a novel EMD–ENN approach, a hybrid of empirical mode decomposition (EMD) and Elman neural network (ENN), is proposed to forecast wind speed. First, the original wind-speed datasets are decomposed into a collection of intrinsic mode functions and a residue by EMD, yielding relatively stationary sub-series that can be readily modeled by neural networks. Second, both intrinsic mode function components and residue are applied to establish the corresponding ENN models. Then, each sub-series is predicted using the corresponding ENN. Finally, the prediction values of the original wind- speed datasets are calculated by the sum of the forecasting values of every sub-series. Moreover, in the ENN modeling process, the neuron number of the input layer is determined by a partial autocorrelation function. Four prediction cases of wind speed are used to test the performance of the proposed hybrid approach. Compared with the persistent model, back-propagation neural network, and ENN, the simulation results show that the proposed EMD–ENN model consistently has the minimum statistical error of the mean absolute error, mean square error, and mean absolute percentage error. Thus, it is concluded that the proposed approach is suitable for wind-speed prediction.

The wind-speed forecasting plays an important role in the planning, controlling and monitoring of the intelligent wind power systems. Since the wind- speed signal is stochastic and intermittent, it is difficult to achieve their satisfactory prediction. In [19], a novel hybrid deep-learning wind-speed prediction model, which combines the empirical wavelet transformation and two kinds of recurrent neural network, is proposed. In the proposed new model, the empirical wavelet transformation is adopted to decompose the raw wind-speed data into several sub-layers. The long short term memory neural network, a deep-learning algorithm-based method, is utilized to predict the low-frequency wind-speed sub-layers. An Elman neural network, a mainstream recurrent neural network, is built to predict the high-frequency sub-layers. In the executed forecasting experiments, eleven different forecasting models are included to validate the real prediction performance of the proposed model. The experimental results indicate that the proposed model has satisfactory performance in the high-precision wind-speed prediction.

The paper [20] presents an in-flight initial alignment method for the guided projectiles, obtained after launching, and utilizing the characteristic of the inertial device of a strapdown inertial navigation system. This method uses an Elman neural network algorithm, optimized by genetic algorithm in the initial alignment calculation. The algorithm is discussed in details and applied to the initial alignment process of the proposed guided projectile. Simulation results show the advantages of the optimized Elman neural network algorithm for the initial alignment problem of the strapdown inertial navigation system. It can not only obtain the same high-precision alignment as the traditional Kalman filter but also improve the real-time performance of the system.

The existence of periodic solutions is a classical problem of the qualitative theory of differential and difference equations. Numerous papers have been devoted to the existence of periodic solutions to different kinds of neural networks with continuous and discrete time.

In our recent paper [21], for a modified Elman neural network with a periodic input, we obtained sufficient conditions for the existence of a periodic output by using Mawhin's continuation theorem of the coincidence degree theory [22]. In our contribution [23], examples were given of Elman neural networks satisfying these sufficient conditions. Periodic solutions were found for particular choices of the weights, self-feedback factors and periodic inputs.

The present paper is an extension of the contribution [23]. Sufficient conditions are obtained for the global asymptotic stability of a periodic output. The periodic outputs corresponding to the periodic solutions previously found are shown to be globally asymptotically stable solutions in the case of continuous transfer functions of the output layer.

2. Existence of Periodic Solutions

We consider a modified Elman network with r nodes in the input layer, n nodes in the hidden and context layers, respectively, and m nodes in the output layer which adds a self-feedback factor α, $0 < \alpha < 1$, in the context nodes, based on the traditional Elman neural network [7-8]. Its mathematical model is

$$x_i(k) = f_i\left(\sum_{j=1}^{n} a_{ij} x_j^C(k) + \sum_{j=1}^{r} b_{ij} u_j(k-1)\right), \qquad (1)$$

$$x_i^C(k) = \alpha x_i^C(k-1) + x_i(k-1), i = \overline{1,n}, \qquad (2)$$

$$y_i(k) = g_i\left(\sum_{j=1}^{n} c_{ij} x_j(k)\right), i = \overline{1,m}, \qquad (3)$$

for $k \in \mathbb{N}$. Here u is the input, x is the output of the hidden layer, x^C is the output of the context layer, and y is the output of the output layer. The weights a_{ij}, b_{ij}, and c_{ij} respectively of the context nodes, input nodes, and hidden nodes are the entries of $n \times n$-, $n \times r$-, and $m \times n$-dimensional matrices, respectively; f_i are the transfer functions of the hidden layer often taken as sigmoid functions, g_i are the transfer functions of the output layer and are often taken as linear functions.

Clearly, for a given input $u(k)$, $k \in \{0\} \cup \mathbb{N}$, and initial values $x(0), x^C(0)$ we can find the output $y(k), k \in \mathbb{N}$, from system (1)-(3).

Now suppose that the input $u(k)$ is N-periodic for some $N \in \mathbb{N}$, that is, $u(k+N) = u(k)$, $k \in \{0\} \cup \mathbb{N}$. We are looking for an N-periodic output $y(k)$, $k \in \mathbb{N}$. This means that for a suitable choice of the initial values $x(0), x^C(0)$ the output $y(k)$ is N-periodic. For this purpose, it suffices that the output $x(k)$ of the hidden layer is N-periodic.

We make the following assumptions:

A1 There exist positive constants L_i, $i = \overline{1,n}$, such that

$$|f_i(x_i) - f_i(\tilde{x}_i)| \le L_i |x_i - \tilde{x}_i|$$

for all $x_i, \tilde{x}_i \in \mathbb{R}, i = \overline{1,n}$.

A2 The following inequality holds:

$$\min_{i=\overline{1,n}}\left(1 - \frac{1}{1-\alpha}\sum_{j=1}^{n} L_j |a_{ji}|\right) > 0$$

In order to formulate our last assumption, we introduce the $n \times n$-matrix

$$\mathcal{A} = \left(\delta_{ij} - \frac{L_i}{1-\alpha}|a_{ij}|, i,j = \overline{1,n}\right),$$

where δ_{ij} is the Kronecker delta, and assume that

A3 The matrix $\mathcal{A}$ is an M-matrix.

Assumption **A3** implies that the matrix $\mathcal{A}$ is nonsingular and its inverse has only nonnegative entries [24, 25].

The main result of [21] is the following theorem.

Theorem 1. *Suppose that assumptions **A1-A3** hold. Then the system of equations (1), (2) has at least one N-periodic solution $x(k)$.*

Theorem 1 is proved using Mawhin's continuation theorem of coincidence degree theory [22].

3. Examples

Consider a modified Elman neural network with $r = 2$, $n = 3$ and $m = 4$ (see Fig. 1).

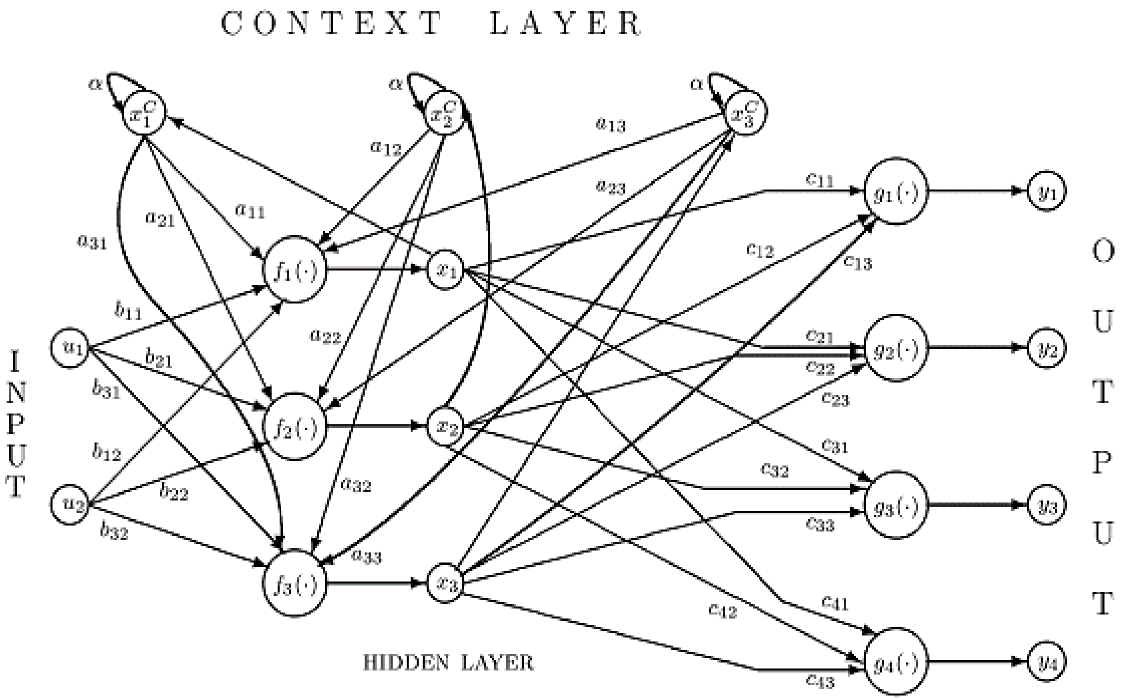

Fig. 1. An Elman neural network with $r = 2$, $n = 3$ and $m = 4$.

Suppose that $\alpha = \frac{1}{2}$, the transfer functions $f_i(x)$, $i = \overline{1,3}$, of the hidden layer all equal the sigmoid function $f(x) = = \frac{1}{1+e^{-x}}$, u_1, u_2 are arbitrary N-periodic functions for some positive integer N, say,

$$u_1(k) = k - \left[\frac{k}{N}\right]N, u_2(k) = k + 1 - \left[\frac{k}{N}\right]N,$$

$k \in \{0\} \cup \mathbb{N}$, where $[v]$ is the greatest integer in the real number v, that is,

$$u_1(0) = 0, u_1(1) = 1, \dots, u_1(N-1) = N-1,$$
$$u_1(N) = 0,\ u_1(N+1) = 1, \quad \dots, u_1(2N-1) =$$
$$= N-1, u_1(2N) = 0, u_1(2N+1) = 1, \dots;$$

$$u_2(0) = 1, u_2(1) = 2, \dots, u_2(N-1) = N,$$
$$u_2(N) = 1,\ u_2(N+1) = 2, \quad \dots, u_2(2N-1) =$$
$$= N, u_2(2N) = 1, u_2(2N+1) = 2, \dots$$

a) Further on, let us assume, for the sake of simplicity, that the weights a_{ij}, $i,j = \overline{1,3}$, of the context nodes all equal $\frac{1}{2}$, the transfer functions g_i, $i = \overline{1,4}$, the weights b_{ij}, $i = \overline{1,3}$, $j = \overline{1,2}$, of the input nodes, and c_{ij}, $i = \overline{1,4}$, $j = \overline{1,3}$, of the hidden nodes are arbitrary.

Then, assumption **A1** is satisfied with $L_i = \frac{1}{4}$, $i = \overline{1,3}$, assumption **A2** is also satisfied since

$$1 - \frac{1}{1-\alpha}\sum_{j=1}^{3} L_j|a_{ji}| = \frac{1}{4}, i = \overline{1,3}$$

Finally, the matrix

$$\mathcal{A} = \begin{pmatrix} \frac{3}{4} & -\frac{1}{4} & -\frac{1}{4} \\ -\frac{1}{4} & \frac{3}{4} & -\frac{1}{4} \\ -\frac{1}{4} & -\frac{1}{4} & \frac{3}{4} \end{pmatrix}$$

is an M-matrix with inverse

$$\mathcal{A}^{-1} = \begin{pmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{pmatrix}$$

Since all assumptions of Theorem 1 are satisfied, the modified Elman neural network under consideration has an N-periodic output $y(k)$, $k \in \mathbb{N}$.

Let us assume that, moreover, $b_{ij} = \frac{1}{2}$, $i = \overline{1,3}$, $j = \overline{1,2}$, and $N = 3$. Then, the system of equations (1), (2) takes the form

$$x_i(k) = f\left(\frac{1}{2}\left(\sum_{j=1}^{3} x_j^C(k) + \sum_{j=1}^{2} u_j(k-1)\right)\right), \qquad (4)$$

$$x_i^C(k) = \frac{1}{2}x_i^C(k-1) + x_i(k-1), \qquad (5)$$

$$k \in \mathbb{N}, \quad i = \overline{1,3},$$

where

$$u_1(k) = \begin{cases} 1, & k \equiv 1 \ (\mathrm{mod}\ 3), \\ 2, & k \equiv 2 \ (\mathrm{mod}\ 3), \\ 0, & k \equiv 0 \ (\mathrm{mod}\ 3) \end{cases}$$

$$u_2(k) = \begin{cases} 2, & k \equiv 1 \ (\mathrm{mod}\ 3), \\ 3, & k \equiv 2 \ (\mathrm{mod}\ 3), \\ 1, & k \equiv 0 \ (\mathrm{mod}\ 3) \end{cases}$$

It suffices to find the initial values $x_i(0)$, $x_i^C(0)$, $i = \overline{1,3}$, so that

$$x_i^C(3) = x_i^C(0), x_i(3) = x_i(0), \qquad i = \overline{1,3} \qquad (6)$$

Equations (4), (5) imply that

$$x_1(k) = x_2(k) = x_3(k), \qquad k \in \mathbb{N},$$

and

$$x_1^C(k) = x_2^C(k) = x_3^C(k), \qquad k = 2,3, \ldots$$

Thus, in order to satisfy equations (6), the initial conditions must be chosen so that

$$x_1(0) = x_2(0) = x_3(0)$$

and

$$x_1^C(0) = x_2^C(0) = x_3^C(0)$$

System (4), (5) reduces to

$$x(k) = \\ = f\left(\frac{1}{2}\left(3x^C(k) + u_1(k-1) + u_2(k-1)\right)\right), \qquad (7)$$

$$x^C(k) = \frac{1}{2}x^C(k-1) + x(k-1), \qquad k \in \mathbb{N} \qquad (8)$$

We have found that the initial values $x^C(0), x(0)$ satisfying (6) are (approximately)

$$x^C(0) = 1.9634, x(0) = 0.9810$$

The first 4 values of the 3-periodic solution of system (7), (8) are presented in Table 1.

Table 1. A 3-periodic solution of system (7), (8).

	$k=0$	$k=1$	$k=2$	$k=3$
$x^C(k)$	1.9634	1.9627	1.9504032	1.9633761
$x(k)$	0.9810	0.9690532	0.9881745	0.9810172

b) Next, let us assume that $a_{11} = \frac{1}{2}$, $a_{12} = a_{22} = = \frac{1}{4}$, $a_{13} = a_{21} = a_{33} = \frac{1}{8}$, $a_{23} = a_{31} = \frac{1}{16}$, $a_{32} = \frac{1}{32}$, the transfer functions $g_i, i = \overline{1,4}$, the weights b_{ij}, $i = \overline{1,3}, j = \overline{1,2}$, of the input nodes and c_{ij}, $i = = \overline{1,4}, j = \overline{1,3}$, of the hidden nodes are still arbitrary.

Then, assumption **A1** is still satisfied with $L_i = \frac{1}{4}, i = \overline{1,3}$, assumption **A2** is also satisfied since

$$1 - \frac{1}{1-\alpha}\sum_{j=1}^{3} L_j |a_{j1}| = \frac{5}{16},$$

$$1 - \frac{1}{1-\alpha}\sum_{j=1}^{3} L_j |a_{j2}| = \frac{47}{64},$$

$$1 - \frac{1}{1-\alpha}\sum_{j=1}^{3} L_j |a_{j3}| = \frac{27}{32}$$

Finally, the matrix

$$\mathcal{A} = \begin{pmatrix} \frac{3}{4} & -\frac{1}{8} & -\frac{1}{16} \\ -\frac{1}{16} & \frac{7}{8} & -\frac{1}{32} \\ -\frac{1}{32} & -\frac{1}{64} & \frac{15}{16} \end{pmatrix}$$

is an M-matrix with inverse

$$\mathcal{A}^{-1} = \begin{pmatrix} 1.3536229 & 0.1951023 & 0.0967449 \\ 0.0983574 & 1.1577144 & 0.0451476 \\ 0.0467601 & 0.0257986 & 1.070644 \end{pmatrix}$$

Since all assumptions of Theorem 1 are satisfied, the modified Elman neural network under consideration has an N-periodic output $y(k)$, $k \in \mathbb{N}$.

Let us assume that, moreover, $b_{11} = \frac{1}{2}$, $b_{12} = = b_{21} = \frac{1}{3}$, $b_{22} = b_{31} = \frac{1}{4}$, $b_{32} = \frac{1}{8}$, and $N = 3$. Then, the system of equations (1), (2) takes the form

$$x_i^C(k) = \frac{1}{2}x_i^C(k-1) + x_i(k-1), k \in \mathbb{N}, i = \overline{1,3},$$

$$\left.\begin{aligned} x_1(k) &= f\left(\frac{1}{2}x_1^C(k) + \frac{1}{4}x_2^C(k) + \frac{1}{8}x_3^C(k) + \frac{1}{3}\right) \\ x_2(k) &= f\left(\frac{1}{8}x_1^C(k) + \frac{1}{4}x_2^C(k) + \frac{1}{16}x_3^C(k) + \frac{1}{4}\right) \\ x_3(k) &= f\left(\frac{1}{16}x_1^C(k) + \frac{1}{32}x_2^C(k) + \frac{1}{8}x_3^C(k) + \frac{1}{8}\right) \end{aligned}\right\}$$
$$k \equiv 1 \pmod 3,$$

$$\left.\begin{aligned} x_1(k) &= f\left(\frac{1}{2}x_1^C(k) + \frac{1}{4}x_2^C(k) + \frac{1}{8}x_3^C(k) + \frac{7}{6}\right) \\ x_2(k) &= f\left(\frac{1}{8}x_1^C(k) + \frac{1}{4}x_2^C(k) + \frac{1}{16}x_3^C(k) + \frac{5}{6}\right) \\ x_3(k) &= f\left(\frac{1}{16}x_1^C(k) + \frac{1}{32}x_2^C(k) + \frac{1}{8}x_3^C(k) + \frac{7}{8}\right) \end{aligned}\right\}$$
$$k \equiv 2 \pmod 3,$$

$$\left.\begin{aligned} x_1(k) &= f\left(\frac{1}{2}x_1^C(k) + \frac{1}{4}x_2^C(k) + \frac{1}{8}x_3^C(k) + 2\right) \\ x_2(k) &= f\left(\frac{1}{8}x_1^C(k) + \frac{1}{4}x_2^C(k) + \frac{1}{16}x_3^C(k) + \frac{17}{12}\right) \\ x_3(k) &= f\left(\frac{1}{16}x_1^C(k) + \frac{1}{32}x_2^C(k) + \frac{1}{8}x_3^C(k) + \frac{1}{2}\right) \end{aligned}\right\}$$
$$k \equiv 0 \pmod 3$$

It suffices to find the initial values $x(0), x^C(0)$, so that

$$x(3) = x(0), \qquad x^C(3) = x^C(0)$$

We have found that, approximately,

$$x_1^C(0) = 1.8403, \qquad x_2^C(0) = 1.614,$$
$$x_3^C(0) = 1.3689, \qquad x_1(0) = 0.9705,$$
$$x_2(0) = 0.89425, x_3(0) = 0.77054$$

(see Table 2 for the first 4 values of the 3-periodic solution of the above system).

Table 2. A 3-periodic solution in Case b).

	$k=0$	$k=1$	$k=2$	$k=3$
$x_1^C(k)$	1.8403	1.89065	1.813606	1.8400157
$x_2^C(k)$	1.614	1.70125	1.5821907	1.6145067
$x_3^C(k)$	1.3689	1.45499	1.3448186	1.3689537
$x_1(k)$	0.9705	0.868281	0.9332127	0.9705381
$x_2(k)$	0.89425	0.7315657	0.8234114	0.8943396
$x_3(k)$	0.77054	0.6173236	0.6965444	0.7705772

The initial values in Cases a) and b) have been found using MATLAB, after numerous experiments with different sets of possible initial values.

4. Global Asymptotic Stability of Periodic Solutions

For $x = (x_1, x_2, \ldots, x_n)^T$ we denote

$$|x| := \sum_{i=1}^{n} |x_i|$$

For convenience, we write equation (3) in the form

$$y(k) = \hat{g}(x(k)), \qquad k \in \{0\} \cup \mathbb{N},$$

where the function $\hat{g}: \mathbb{R}^n \to \mathbb{R}^m$ is defined by

$$\hat{g}(x) = (\hat{g}_1(x), \ldots, \hat{g}_m(x))^T$$

and

$$\hat{g}_i(x) = g_i\left(\sum_{j=1}^{n} c_{ij} x_j\right), i = \overline{1,m}$$

An N-periodic solution $\tilde{y}(k) = \hat{g}(\tilde{x}(k))$ of the system (1)-(3) is said to be *globally asymptotically stable* if for any other solution $y(k) = \hat{g}(x(k))$ of system (1)-(3) we have

$$\lim_{k\to\infty} |y(k) - \tilde{y}(k)| = 0$$

Theorem 2. *Suppose that assumptions* ***A1, A2*** *hold. If the functions $g_i, i = \overline{1,m}$, are continuous, then any N-periodic solution $\tilde{y}(k)$ of system (1)-(3) is globally asymptotically stable.*

Proof. Since $\tilde{x}(k)$ is N-periodic, the set

$$\{\tilde{x}(k), k \in \{0\} \cup \mathbb{N}\}$$

contains at most N distinct points

$$\tilde{x}(0), \tilde{x}(1), \ldots, \tilde{x}(N-1)$$

Let $K \subset \mathbb{R}^n$ be a compact set containing these points together with their open δ-neighbourhoods for some $\delta > 0$. The function $\hat{g}$ is uniformly continuous on the compact set K, thus for any $\varepsilon > 0$ there exists $\delta_1 \in (0, \delta)$ such that $|\hat{g}(x) - \hat{g}(\tilde{x}(k))| < \varepsilon$ when $|x - \tilde{x}(k)| < \delta_1$ for some $k \in \{0,1,\ldots,N-1\}$. Thus, for the N-periodic solution $\tilde{y}(k) = \hat{g}(\tilde{x}(k))$ of system (1)-(3) and any other solution $y(k) = = \hat{g}(x(k))$ of system (1)-(3), it suffices to show that

$$\lim_{k\to\infty} |x(k) - \tilde{x}(k)| = 0 \qquad (9)$$

Let us denote

$$q := \max_{i=\overline{1,n}} \left(\alpha + \sum_{j=1}^{n} L_j |a_{ji}|\right)$$

From assumption **A2**, it follows that $q \in (0,1)$.

From equation (1) and assumption **A1**, we find

$$|x_i(k) - \tilde{x}_i(k)| \leq L_i \sum_{j=1}^{n} |a_{ij}| \, |x_j^C(k) - \tilde{x}_j^C(k)|$$

Summing up these inequalities for $i = \overline{1, n}$, we deduce

$$|x(k) - \tilde{x}(k)| \leq \sum_{i=1}^{n} L_i \sum_{j=1}^{n} |a_{ij}| \, |x_j^C(k) - \tilde{x}_j^C(k)| =$$
$$= \sum_{i=1}^{n} \left(\sum_{j=1}^{n} L_j |a_{ji}| \right) |x_i^C(k) - \tilde{x}_i^C(k)|$$

Adding together the last inequality and

$$\alpha |x^C(k) - \tilde{x}^C(k)| \leq \alpha \sum_{i=1}^{n} |x_i^C(k) - \tilde{x}_i^C(k)|,$$

we obtain

$$|x(k) - \tilde{x}(k)| + \alpha |x^C(k) - \tilde{x}^C(k)| \leq$$
$$\leq \sum_{i=1}^{n} \left(\alpha + \sum_{j=1}^{n} L_j |a_{ji}| \right) |x_i^C(k) - \tilde{x}_i^C(k)| \leq$$
$$\leq q |x^C(k) - \tilde{x}^C(k)| \leq$$
$$\leq q(|x(k-1) - \tilde{x}(k-1)| +$$
$$+ \alpha |x^C(k-1) - \tilde{x}^C(k-1)|)$$

for $k \in \mathbb{N}$. These inequalities imply

$$|x(k) - \tilde{x}(k)| + \alpha |x^C(k) - \tilde{x}^C(k)| \leq$$
$$\leq q^k (|x(0) - \tilde{x}(0)| + \alpha |x^C(0) - \tilde{x}^C(0)|)$$

for $k \in \mathbb{N}$, hence

$$\lim_{k \to \infty} (|x(k) - \tilde{x}(k)| + \alpha |x^C(k) - \tilde{x}^C(k)|) = 0$$

In particular, the last equality implies (9), and Theorem 2 is proved. □

Theorem 2 shows that the 3-periodic solutions obtained in Section 3 are globally asymptotically stable solutions of system (1), (2). If the transfer functions of the output layer are continuous, then the respective periodic outputs $y(k)$ are globally asymptotically stable.

7. Conclusions

We found periodic solutions of modified Elman neural networks satisfying the respective sufficient conditions. If the transfer functions of the output layer are continuous, the respective periodic outputs are globally asymptotically stable. In our subsequent paper [26], we considered similar problems for output-hidden feedback Elman neural networks. The model considered can be applied to the services quality of experience prediction.

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Recent Metha-Heuristic Algorithms in High Induction Motor Design: A Comparison Study

Hania LADAYCIA
University of 20 Août 1955, Department of Electrical Engineering, Skikda, Algeria
Tel.: + 213795770990, + 213676769423
E-mail:hania_ladaycia@live.fr

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Abstract: The design of the electrical machines is a complicated process. On top of that, it follows the objective physical and mathematical principles, but on the other hand, knowledge of these principles is often insufficient to produce a correct and economic design, and must be complete by considerable judgment, rules of thumb and experience which can be acquired only after intensive training on the job. This paper carries out efficiency optimization of 37 kW, 380 V, 1800 synchronous r.p.m., three phase squirrel cage induction motor (SCIM) using two swarm intelligence techniques Firefly algorithm (FA) and accelerated particle swarm optimisation (APSO). A comparison between APSO and FA swarm techniques is done. Efficiency and power factor are achieved to the goal and efficiency results satisfies high efficiency level (IE 2 class > 93.0%). APSO is the best method for optimization in comparison with FA if efficiency is to be optimized.

Keywords: Metaheuristic, Design, Induction motor, High efficiency.

1. Introduction

Electric motors consume over half of the energy produced by power stations. This represents almost three-quarters of industrial consumption and almost half of the consumption of commercial sectors in industrialised countries. Motors therefore represent the most significant electrical loads and are therefore the main targets for achieving significant energy savings [1-2].

The design of asynchronous motors covers a very wide field of activity, ranging from machines with a few watts of power intended for computer applications to a motor with a few megawatts installed in heavy industrial processes. This type of machine represents a large part of the electrical machinery market, especially squirrel-cage machines, are the most commonly used electrical machines [3]. Considerable efforts have been and still are being made to perfect the theory and methods of analysis and designs thereof, in order to improve its performance and optimise its price [1-15].

2. Proposed Method

In this work we present an optimal design method to optimize the three-phase induction motor in the manufacturing process. The APSO and FA have been adapted to optimize its design to improve its performances. The motor design procedure consists of a system of nonlinear equations imposing the characteristics of the induction motor, motor performances, magnetic stresses and thermal limits.

The results of the computer simulation are given to show the efficiency of the proposed design process and the optimization techniques applied.

3. Problem Formulation

APSO and FA are implemented with the direct design described in [12] formulated by the following equation:

$$\begin{cases} \min \sum losses(D_{is}, d_1, d_2, h_r, b_{tr}, b_{ts}, b_{s1}, b_{s2}, h_s) \\ s.t. \quad \cos\varphi \geq 0.861 \\ \quad \eta \geq 0.936 \\ \quad T_{c0} \leq 101 \\ \quad i_{LR} \leq 6 \\ \quad t_{LR} \geq 1.75 \\ \quad t_{bk} \leq 2.5 \\ \quad D_{out} = 343 \\ \quad D_{shaft} = 70 \end{cases} \quad (1)$$

D_{is} is the stator bore diameter, d_1 is the rotor slot higher diameter, $d_2$is the rotor slot lower diameter, h_r is the rotor slot useful height, b_{tr} is the rotor tooth width,b_{ts} is the stator tooth width, $b_{s1}$is the stator slot lower width, b_{s2} is the stator slot higher width, h_s is the stator slot useful height, η is the efficiency, T_{c0} is the winding temperature, i_{LR} is the per unit locked rotor current, $t_{bk}$is the per unit breakdown torque, D_{out} is the stator outer diameter, D_{shaft} is the shaft diameter.

Where losses is the total losses in induction motor defined by:

$$\sum lossees = P_{c0} + P_{Al} + P_{iron} + P_{mv} + P_{sup} \quad (2)$$

P_{c0} are stator copper loss, P_{Al} are the rotor Aluminum loss, P_{iron} are the iron loss, P_{mv} are the frictionand windage loss and P_{sup} are the stray load loss.

Table 1 shows the brief specification of 37 kW three phase induction motor for optimizing design. The inner diameter of stator and shaft are fixed respectively for assembling prototype [16].

Table 1. Induction motor specification.

Designation	Value
Phase number	3
Input voltage [V]	380
Frequency [Hz]	60
Output power [kW]	37
Pole number	4
Stator out diameter [mm]	343
Shaft diameter [mm]	70

4. Accelerated Particle Swarm Optimization (APSO)

Accelerated Swarm Optimization (APSO) was developed by Xin She Yang in 2008 is a population-based stochastic optimization technique and a simplified version that uses both the best current global and the best individual. The aim of the optimal use of the individual is to increase the diversity of quality solutions. APSO could accelerate the convergence of the algorithm is to use only, the best overall. Thus, in the APSO each particle is attracted by the position of the best current global gbest and its best pbest location of history, while tending to move randomly. When a particle finds a better location than all previously found locations, it updates it as the best current for particle i. There is a best current for all n particles at any time t during iterations. The objective is to find the best overall of all the best current solutions until the objective no longer improves or after a number of iterations [17].

The typical values for this APSO are $\alpha \approx 0.1{\sim}0.4and\beta \approx 0.1{\sim}0.7$; however, $\alpha \approx 0.2$ and $\beta \approx 0.5$ are recommended [18]. In general, any stochastic search algorithm shows improved performance with a relatively larger population. Nevertheless, a very large population will cost more in terms of fitness function evaluations without producing significant improvements. In this simulation, the population size is set to 150.

In APSO [19], the speed vector is generated by a simple formula given by the Eq. (3):

$$v_i^{t+1} = v_i^t + \alpha\xi_n + \beta(gbest - x_i^t) \quad (3)$$

5. Firefly Algorithm

Firefly algorithm is one of recent metaheuristic nature-inspired algorithm, which was developed by Dr. Xin-She Yang at Cambridge University in 2007. Whereas this algorithm has some similarities with other algorithms based on the collective intelligence of the group such as PSO, but relatively speaking this algorithm is relatively simple in theory and implementation. And the most prominent advantage is the use of the random movement of individuals, taking into account the mutual influence between individuals at the same time. Some recent literatures show that the algorithm is very effective in solving some optimization problems and can be better than the other traditional algorithms. And the stability of the firefly algorithm proved to be superior to other well-known optimization algorithm [20].

The firefly algorithm is inspired by the flashing behaviour of fireflies. The movement of each Firefly is guided by its flashing pattern and attraction strategy. The algorithm takes into account the tree following points [21]:

- All fireflies are unisex so that one Firefly is attracted to other fireflies regardless of their sex.
- Attractiveness is proportional to brightness, so for any two flashing fireflies, the less bright Firefly will move towards the brighter Firefly. Both attractiveness and brightness decrease as the distance between fireflies increases. If there is no Firefly brighter than a particular Firefly, that Firefly will move randomly.
- The brightness of a Firefly is affected or determined by the landscape of the objective function.

The movement equation of a less bright Firefly *I* attracted by a brighter firefly *j* is determined by:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}(x_j - x_i) + \alpha\left(rand - \frac{1}{2}\right), \qquad (4)$$

where r_{ij} is the cartesian distance between two fireflies *i* and *j*. it is defined by:

$$r_{ij} = \sqrt{\sum_{k=1}^{d}(x_{i,j} - x_{j,k})^2}, \qquad (5)$$

β_0 is the attractiveness at $r = 0$, α is a random parameter and parameter γ characterizes the variation of the attractiveness.

6. Simulation Results

The change of objective function values according to the iteration is shown in Fig. 1. It is seen that the APSO method converges at the smallest iteration number. The APSO algorithm converges at the 29th iteration. However, FA algorithm converges at the 127th iteration.

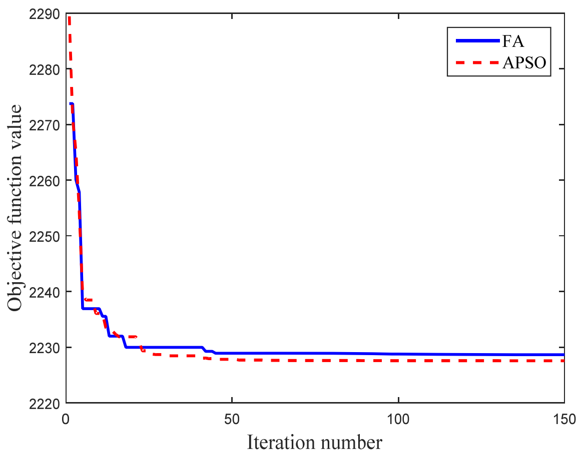

Fig. 1. Iteration number versus the objective function value.

The performances and the optimal design variables of the motor obtained with the two methods are given in Table 2.

It is clear from the table that the APSO is able to offer the better efficiency and the desired power factor than that of the FA approach.

Fig.2 represent the variation of efficiency vs. shaft torque for three different techniques APSO, FA and conventional technique. APSO and FA methods are seen to have caught the actual values with very small differences. It is also observed that the values of the efficiency satisfies high efficiency level (IE 2 class > 93.0%) for the three techniques. The values obtained by APSO and FA are close to the target value.

Table 2. Comparison of the results obtained by the FA and APSO methods for a 37kW SCIM.

Designation	Conception conventional	FA	APSO
D_{is} [mm]	221	215	215
d_1 [mm]	7.3477	7.5	7.5
d_2 [mm]	2.8419	2.5	2.5
b_{s1}	6.5195	5.2430	5.289712
b_{s2}	10.3856	8.7699	8.943088
h_r [mm]	28.6257	28.7	28.69998
b_{tr} [mm]	9.2754	5.0420	5
b_{ts}[mm]	8.2721	4.4	4.4
h_s [mm]	29.4923	28.3769	28.03786
i_{LR}	5.9638	5.9812	5.9959
t_{LR}	0.9928	0.9964	1.0008
t_{bk}	2.9135	2.9278	2.9323
Power factor [%]	86.44	86.18	86.18
Efficiency [%]	93.23	93.51	93.52
T° of winding [°C]	112.2971	113.2397	113.8508

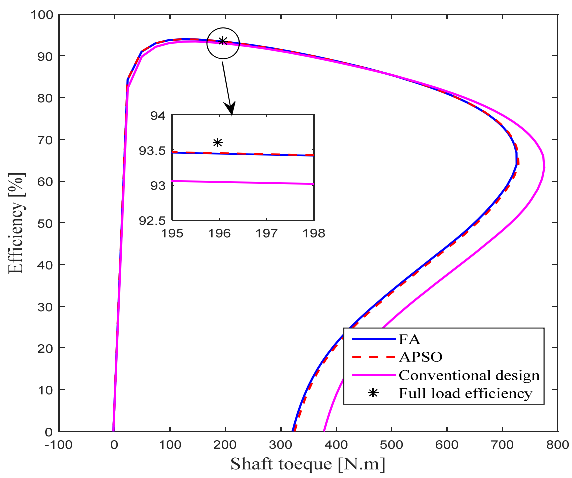

Fig. 2. Efficiency-Shaft torque characteristic after optimization.

The change of objective function value according to the number of trial is shown in Fig. 3 for the two methods APSO and FA. It is seen that the values obtained by the FA as a result of 30 operations are bigger than the values obtained by the APSO. It is seen that the maximum fitness value is obtained by the FA at the 20th operation, and the minimum fitness value is obtained at the 1st operation by the APSO. However, the lowest fitness values is obtained by FA at the 23th operation.

The CPU times obtained by the 30 operations of the two methods are given in Fig. 4. It is seen that the FA has the longest solution time and the APSO has the shortest solution time. The solution times of the APSO methods are seen to be less than 1 s. While the FA method reached two seconds.

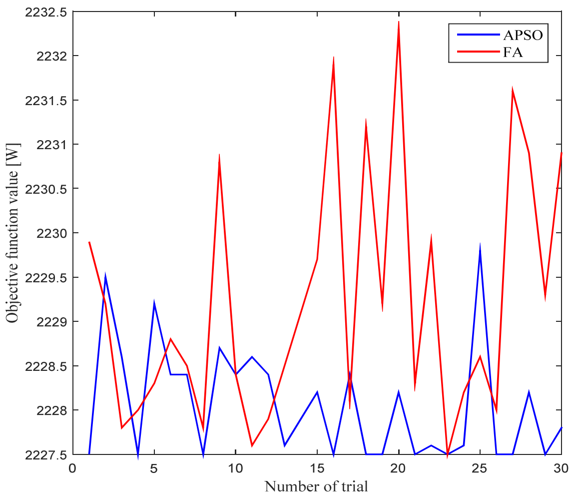

Fig. 3. Distribution of the total loss of the two methaheuristic.

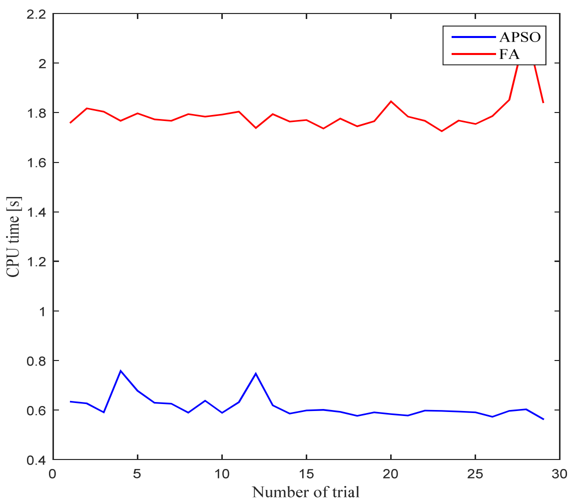

Fig. 4. Distribution of the CPU time of the two methaheuristic.

7. Conclusions

APSO and FA are two powerful populations based heuristic algorithms for solving multimodal optimisation problems. The results of SCIM performances clearly demonstrate the ability of the APSO and FA to produce the best global design parameters that maximise its efficiency and starting torque as well. It has been exhibited that the proposed approaches encourage the continued use of APSO and will go a long way in serving as a useful tool in design problems.

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Increasing Measurement Trustworthiness as a Necessary Part of Technology Development

*** Kseniia SAPOZHNIKOVA, Anton PRONIN and Roald TAYMANOV**
D. I. Mendeleyev Institute for Metrology, 19 Moskovsky pr., Saint Petersburg, 190005, Russian Federation
* Tel.: +7 921 306 61 26, fax: +7 812 713 01 14
* E-mail: k.v.s@vniim.ru

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Abstract: The authors have analysed the development trends of the main technologies related to the application features of measuring instruments (MIs) and multichannel measuring systems (MMSs) as well as provision of their trustworthiness. The analysis has made it possible to propose a methodology for automatic checking metrological health of MIs and MMSs in the course of their operation, which was called "metrological self-check". The self-check enables calibration / verification intervals to be significantly increased. In case of virtual test and artificial intelligent application, automation of the trustworthiness provision becomes possible for traditional measurements. It has been shown that the problem of trustworthiness related to soft measurements taking into consideration the growing interest in them, also becomes actual.

Keywords: Industry 4.0, Measurement trustworthiness, Metrological self-check, Digital twin, Virtual tests, Artificial intelligence, Soft measurement.

1. Introduction

Provision of measurement trustworthiness is the basis of legal metrology. Measurements plays a meaningful role in communication between people and, in a figurative sense, between human and processes under control. The discrepancy between a measurand value expected by its "recipient" and a real quantity value measured, can lead to undesirable situations, sometimes with tragic consequences.

A fundamental metrology requirement aimed at providing the trustworthiness is as follows: for any sensors and measuring channels (hereinafter, this set is called measuring instruments (MIs)) as well as multichannel measuring systems (MMSs), measurement uncertainty should remain within permissible limits under specified external conditions throughout the lifetime. As a consequence, to check the fulfilment of this requirement, i.e., to check metrological health, is necessary. Since over time, characteristics of any MI are changing due to arisen defects, systematic worsening of material properties, or, e.g., weakening component fasteners, the concepts have originated related to periodic calibration / verification and intervals between such procedures.

These procedures involve the cost of their implementation. In the course of human civilisation development, methods of measurements and MI technologies have been improved, the number and accuracy of MIs being increased. Accordingly, the total costs on the metrological health maintenance have increased; to reduce them has been desirable. As a result, the evolution process of trustworthiness provision methods has become an organic part of technology development.

The pace of technology development at the second part of the 20th century and beginning of the 21st century is many times higher than that inherent in the earlier period. The analysis of correlations between technology development stages, on the one hand, and features of the methods for measurement trustworthiness provision, which were developed during these stages, on the other hand, gives the basis for revealing the regularities of the considered process. Looking under this angle, to foresee new tasks in this field, which specialists in metrology will face in the near and more distant future, becomes possible.

This paper is an extended version of the paper presented at the ARCI'2021 [1].

2. Provision of Measurement Trustworthiness as a Part of Technology Development in the 20th Century

In the context considered, the most meaningful technological solution that has been applied since the beginning of the 20th century, is conveyor production with the elements of control automation.

Significantly, any forced conveyor shutdown and resulting operation downtime that concern, in particular, carrying out calibration / verification, result in costs due to the output reduction, while the occurrence of a metrological failure in applied MIs leads to supplement costs related to production spoilage.

As a consequence, the requirements for checking the metrological health of MIs used in technological processes, including those embedded in equipment, have arisen. These requirements should have taken into account the possible effects of varying loads on the MI, which depended on a technological process.

Ideally, the procedure should be carried out after a measurement series being fulfilled by the instrument under checking, but without stopping the equipment. The duration of the interval between checking procedures is determined by a permissible value of an expected change in uncertainty during this interval. While choosing the interval, economic losses that will arise in the case of an unhealthy MI eventually can serve as the main criterium. To carry out such a periodic checking is possible based on indirect features, in particular, production features, e.g., to measure the finished part sizes which should correspond to the specified values, is possible [2].

In the years that followed, these technological solutions have been improved and used more and more widely in automatic machinery, power units, transport, including aviation and spacecrafts, in medical technology, etc. The value of metrological failure consequences has been growing up. Accordingly, the requirements for checking have been tightening. In technical systems of high importance, calibration / verification intervals should have been reduced to the values that were significantly lower than those being determined by the expected changes of the measurement uncertainty.

Simultaneously, the human role in automatic control systems (ACSs) was concentrated on the equipment operation failures (e.g., those caused by appearance of untrustworthy measurement information), and prevention of situations which could result in accidents.

The search for new solutions has led to the understanding that the prototype of ACS first emerged in living organisms. Accordingly, evolutionary experience could be useful in improving technologies. Cybernetics has emerged relying upon the analogy between the biological evolution and development of technical systems [3-5]. Then, computer technologies have become a part of production process, which provided tools for ACS improvement.

At the end of the 20th century, the rapid growth in the number of MIs and MMSs included in ACS was noticeable. That process was accompanied by

- The transmission of measurement information over significant distances in order to carry out control operations and
- The wide use of computer technologies including cloud ones for processing measurement information.

The mentioned tendencies have stimulated the search for methodology that allows minimizing costs for provision of measurement trustworthiness by transition to automatic checking the metrological health (metrological self-check / self-validation) of MIs and MMSs [2, 6, 7].

The end of the 20th century has brought strengthening the links between professionals living in various countries. People were increasingly treated or studied abroad. The tendency has been marked to integrate processes across sciences while developing new technologies, in particular, those related to the re-engineering of clinical medicine. The need for provision of metrological traceability and accordingly, of measurement trustworthiness has emerged not only in engineering and physics, but also in chemistry, laboratory medicine, biology, biochemistry, molecular biology, food science, forensic science, etc. All this indicated the arrival of the next technological revolution, which was reflected in the 3rd edition of the International Vocabulary of Metrology [8].

3. Changes in Technology and Associated Metrology Solutions at Industry 4.0 Stage

3.1. Metrological Self-Check in MIs and MMSs

At the stage of Industry 4.0, the range of mass-produced MIs and MMSs noticeably expands. This is especially true with regard to the devices assigned for chemical manufacturing processes and medicine. Among the latter, MMSs automatically forming a medical diagnosis based on many parameters, are of particular interest, e.g., [9, 10]. Accordingly, a variety of methods and means for ensuring measurement trustworthiness increases. For the first time, this statement concerns measurements of multidimensional quantities, the influence of each parameter on the measurement result being not equal.

A noticeable part of MIs and MMSs are produced by small batches. Their cost is high, which, in many cases, excludes the possibility of their duplication. The situation with built-in MIs, e.g., used in hazardous production, is similar. For them, calibration / verification on site, as a rule, is impossible. To deliver the devices to a specialized metrological centre can cause a long downtime. Consequently, it is highly desirable for an owner of these devices to provide their high metrological reliability This will make it possible to maximize the interval during which the owner can be confident in the measurement trustworthiness.

To improve the trustworthiness of measurements, to apply a metrological self-check / self-validation in MIs and MMSs, is necessary [1, 2, 6, 7, 11-13, 14-17]. The use of these methods does not contradict ISO standard [18] that does not limit metrological maintenance methods to traditional ones. The idea of the metrological self-check was proposed in the 1980s [6], but only at the stage of Industry 4.0 its implementation becomes inevitable. The metrological self-check relies on the redundancy that should be revealed or artificially introduced in a MI or MMS.

The applied redundancy can be of spatial (structural), temporal/frequency, functional (informational) character. In some cases, it is expedient to use a combination of two or more types of redundancy in the same MI or MMS. The metrological self-check can be developed in the form of a diagnostic one or direct resembling calibration [19-21]. Moreover, it can be organized both at the level of the MMS as a whole and in separate sensors or measuring channels.

The self-check enables revealing a metrological failure or significant uncertainty growth, which as a consequence, opens the way for the automatic correction of the latter [2, 11, 14, 19].

The self-check methods provide the ground for meaningful extension of calibration / verification intervals. In the event of metrological failure, such methods enable taking measures to eliminate it quickly with the minimum costs.

The diagnostic self-check has resulted in the emergence of a concept “critical uncertainty component” that was new for measurement science. The thing is that the reason of the growing uncertainty can concern several influence quantities. The most dangerous ones cause a predominant or rapidly increasing uncertainty component that is called the critical one [19-20].

To determine it, at the first stage, it is necessary

- To analyze the operation experience of an analogue MI or develop and manufacture a prototype,
- After that, to test this prototype or the analogue for the impact of influencing factors which are considered essential.

At the second stage, the analysis of uncertainty components should be carried out. From them, the component corresponding to the above definition should be singled out. If some of the components can be significantly reduced by changing the design elements of the prototype, to do so is appropriate.

Numerous realisation examples of the metrological self-check (both direct and diagnostic ones) of sensors and MMSs are given in [14-16, 19, 20, 22, 23]. Recently, information on new interesting developments has been published.

In Russia, these themes are of particular actuality since the metrological maintenance of a significant part of MIs and MMSs falls within the scope of the state regulation. Most of the examples below relate to developments fulfilled in Russian organizations.

In particular, Kalashnikov in [24] proposes that the metrological diagnostic self-check of a level meter based on the conductometric principle can be carried out at an NPP by using the functional redundancy.

The main element of this level meter that, in essence, plays the role of MMS, is a set of conductometric cells. The difference of the electric conductivity at the border of fluid and vapour, enables determining the fluid level.

The functional redundancy is realized due to the periodical switching of the conductometric cell set to an EMF measurement mode. In polar fluids, particularly in water, the value of EMF is significant, while in the case of saturated steam, it is equal to zero. By comparing the results of measurements in the conductometric and the EMF measurement modes, to judge about the trustworthiness of level measurements is possible.

The authors of [25] describe the organization of the metrological diagnostic self-check of a sensor assigned for measuring the tension force of reinforcing steel ropes located on the concrete containment of nuclear reactor.

The sensor includes 12 primary transducers and can also be considered as MMS, although the tension force is ultimately determined by the sum of forces measured by individual transducers. In this device, functional redundancy is used. Its basis is the presence of a reference virtual plane that can be constructed taking into account the location of transducers as well as their characteristics. The deviation of output signals of individual transducers from this plane, indicates the change in their metrological characteristics. Accordingly, measurement results are not considered to be trustworthy.

Khodunkov in [26] proposes a self-calibrating temperature sensor comprising a thermoelectric transducer, cold junction unit, microprocessor control unit, and cooling unit of a cold junction unit. Under a wide range of influencing conditions, it can be considered as the sensor with the metrological self-check based on time and functional redundancy. In the sensor, the cold junction unit includes a heater and reference thermosensitive element, cooling device of cold junction unit being installed on thermoelectric transducer head. In the self-check mode, the cold junction is heated, the thermoEMF of the thermoelectric transducer is measured using the microprocessor control unit, while a temperature deviation is determined with the help of the reference thermosensitive element. To calculate the thermoEMF coefficient is possible on the basis of the difference between the thermoEMF values before and after heating as well as temperature deviation. This coefficient should be compared with the calibration parameters. If the obtained value lies within permissible limits, measurement information from the thermoelectric transducer is trustworthy.

In [27], the same author shows the way to improve this sensor operation and turn from a statical version to a dynamic one. The aim is

- To reduce the time interval necessary for self-checking and
- To provide this operation under changing temperature of the environment being measured by the thermoelectric transducer.

To achieve this aim, when the cold junction is heated, both current thermoEMF values of the thermoelectric transducer and the cold junction temperature are registered simultaneously. Then, the time derivatives of these parameters and thermoEMF coefficient taking them into account, are calculated.

A four- channel radiation thermometer [28] developed by Ionov, *et al*. applies the direct self-check (a special lamp that plays the role of a reference standard) and diagnostic one. In this device, the metrological self-check relies upon all the main kinds of redundancy.

By the use of redundancy, the authors reveal and correct the influence of both ageing of the transducers and external factors such as imperfection of object surface, radiation weakening due to atmospheric aerosols as well as absorption of thermal radiation by water vapour.

Koenig in [29] calls analogues functions “self-X capabilitues” and includes, e.g., self-monitoring and self-healing in them. In essence, these concepts correspond to self-check and self-correction, respectively.

As one of the examples, the author considers a magnet rotary encoder. The use of signal harmonics (frequency redundancy) enables providing wide diagnostic capabilities with regard to the signal quality and device parameters.

It follows from the above that application of the metrological self-check is effective in separate MIs and MMSs. However, below there will be shown that the metrological self-check is the most demanded in cyber-physical complexes.

3.2. Metrological Self-check in Cyber-physical Complexes

A characteristic feature of the new technological revolution is the widespread application of cyber-physical complexes. They include “smart manufacturing”, “smart transport”, “smart houses”, “smart cities”, “smart healthcare”, etc. The exploitation life of such complexes before being modernised is highly likely to be estimated not less than 10 years, while common calibration / verification intervals is equal to 1-2 years.

ASC of cyber-physical complexes include computerised MIs and MMSs as the main element. With the present-day instrumentation technologies, there exists a significant probability that the metrological characteristics of the used MIs and MMSs will lie outside the tolerance before they are modernised. As a result, the efficiency of such complexes can be reduced to unacceptable level.

Centralised supply systems for such resources as gas, electricity, water, and petroleum products can be considered as examples. The need for controlling resource flows and measuring their parameters has led to the emergence of appropriate ACSs with numerous MMSs distributed over large areas. In many cases, measurement results obtained in MMS measuring channels are directly or indirectly interlinked. Then, there exists a possibility to organise the metrological self-checking based on the available functional redundancy (at the level of MMSs as a whole).

In particular, to estimate the required resource amount in various districts and maintain ACSs in a serviceable condition, the data on resource consumption received by each customer which is confirmed by device indications, should come to control centres.

If the data from customers do not correspond to the centre data on the resource amount that has come to this district, the measures should be taken on detecting the places where failures occurred. In many cases, the reasons for such a situation can concern metrological failures of sensors or measuring channels of the MMS.

In order to organise the efficient metrological self-check, MMS should be multilevel, each channel from the centre at any level being divided into next level channel groups that transmit the resource to a part of users.

The metrological self-check can be performed with the help of subsystems that link the input MIs of channels related to a previous level with the input MIs of subsequent level channels. These subsystems should carry out checking the correlation between the amount of the transmitted resource and data on summarised resource received by a group of consumers.

In case of discrepancy, the results of such a check will enable automatic localising an unhealthy MI or give grounds to draw the conclusion that, e.g., the reason of the revealed discrepancy is the initiation of the leakage in the channel between the MIs of previous and subsequent levels.

A failure signal that indicates the necessity for a specialist to come and take corrective maintenance should be sent to the centre.

However, in such MMSs, the probability exists that this information will not come to the centre in time due to

- A too prolong cycle of message collection from all measuring channels of the MMS, and
- Malfunction of the message collection sequence.

In order to exclude such a risk and economic losses related to it, when being sent to the centre, each message should receive a priority rank [30], information on more significant failure having a higher one. In this case, the measures for elimination of an occurred failure will be taken promptly with the minimum losses.

Such ACSs with various automation level exist in a number of cities and districts. They are being improved, but no publications concerning the developed metrological self-check in them could be found.

However, according to the information we have, in Saint Petersburg, the work is planned to organize the metrological self-check of city water supply system in 2021.

In analogues systems, as resources are being transmitted to consumers, their amount, density (in case of precipitations), chemical composition (in case of the breach of transmission condition), etc. can change.

The metrological self-check enables quickly determining problems originated as well as their possible reasons with the minimum costs. After that, the methods for troubleshooting can be found.

A characteristic example is considered in [31].

In a centralised system of a megapolis water supply, a bioelectronic system assigned for early diagnostics of sudden drinking water contamination is included. The system applies crayfish as biosensors. Using an optical system, the heart rate is determined for each crayfish which shows whether the water is pure enough.

The proposed method of the metrological self-check is based on the functional redundancy. For a rest state of the crayfish and a healthy measuring channel, the standard deviation (RMS) of the heart rate should be constant within some limits or can decrease. If a significant increase in the RMS within the same frequency range takes place, it can be caused by a decrease in the signal-to-noise ratio that leads to an increase, primarily, in the random measurement error, i.e., to a measurement trustworthiness reduction.

It does not matter whether the reason of this effect is a decrease of the useful signal (due to the decrease in a laser emissivity, degradation of contact quality or optical properties of the shell, contamination of the optical system, change in the position of the crayfish heart, etc.) or an increase in the noise level.

3.3. Virtual Tests

The concept of virtual tests has been widely spread in recent years. Virtual tests can be defined as tests carried out with the help of a digital twin [32, 33]. At present, there exists many definitions of digital twin depending on the application field.

For example, according to the ISO standard [34], a digital twin in manufacturing systems is a "fit for purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization".

The most generalized one is the definition [33]: a digital twin is "a formal digital representation of some asset, process or system that captures attributes and behaviors of that entity suitable for communication, storage, interpretation or processing within a certain context."

In the case of MI and MMS, virtual test can be defined as a tool simulating the state and behaviour of the environment and material system affecting the test object. The examples of digital twins of MIs are given in [35-40].

In preliminary investigations related to the operation condition impact, if the direct testing of the object under study (e.g., spatially separated MIS channels) is extremely difficult or impossible, it is also reasonable to use the digital twin.

In practice, virtual tests can be carried out with the aim to quantitatively estimate such a metrological reliability characteristic of MIs and MMSs as the calibration / verification interval. These tests are reduced to testing

- Transducers included in each MI or MMS channel providing transmission of the measurement information to a data processing unit;
- The data processing unit itself, forming signals for an ACS operator.

Sensors with converters of measuring information to a digital code are not subject to virtual tests. (It is desirable to test them for impacts expected in the process of operation in real mode). Accordingly, the signals from the digital twin at the input of each tested channel must simulate the signals from the sensors in the course of their operation.

Ideally, the digital twin is implemented taking into consideration the sensor characteristics.-However, in a number of cases, the situation takes place that the data related to the operation of the sensors being planned for application are not accessible.

As a possible way, the data that are obtained from slightly different sensors previously operated under the same conditions, can be used. To pay attention to this methodical feature of virtual tests is necessary.

Mainly, such tests are performed by the application of records of the most typical fragments representing measurand changes and their combinations obtained in the course of a close analog operation. Sometimes, these records are supplemented with dangerous combination fragments designed as a result of the mathematical simulation, which take into account rare and/or unlikely situations and impacts.

The resulting estimate of the metrological reliability should correspond to the value sufficient for realising the required calibration / verification interval of the MI or MMS.

In each specific case, interpretation of concepts "the most characteristic fragments" and "dangerous combinations of fragments" is subjective. This circumstance gives the basis to consider virtual tests as a version of "soft" measurements of the quantity characterizing metrological reliability.

Taking into account [41-43], by "soft" the authors imply measurements carried out under conditions of significant definitional uncertainty. This also concerns the considered case. The mentioned association between virtual tests of such a kind and soft measurements enables soft measurement methods to be applied when performing similar virtual tests.

3.4. New Methods of Measurement Trustworthiness Provision. Dynamics of Application

The widespread introduction of the metrological self-check / self-validation concept is delayed because of psychological problems formulated by T. Kuhn's law [44]. The thing is that when self-check is used, the role of metrologists will change dramatically. The volume of routine work associated with calibrations and verifications will significantly decrease. At the same time, the role of metrologists as engineers developing new measurement methods as well as MIs and MMSs that provide the required measurement trustworthiness during long-term service life, should increase. These changes result in the desire of numerous metrologists, especially elderly specialists, to oppose them. However, according to the Kuhn's law, progress is inevitable, as evidenced by the growing interest in this concept which is illustrated by Fig. 1.

The situation is complicated by the fact that the further development of Industry 4.0 is associated with the emerged need to measure the properties that characterize human and society.

Understanding the relevance of extending the boundaries of the measurable was clearly shown at the last IMEKO TC 1 – TC 7 – TC 13 – TC 18 Symposium held in Saint Petersburg in 2019. About one third of presented papers concern the measurements of quantities that before were considered as qualitative properties.

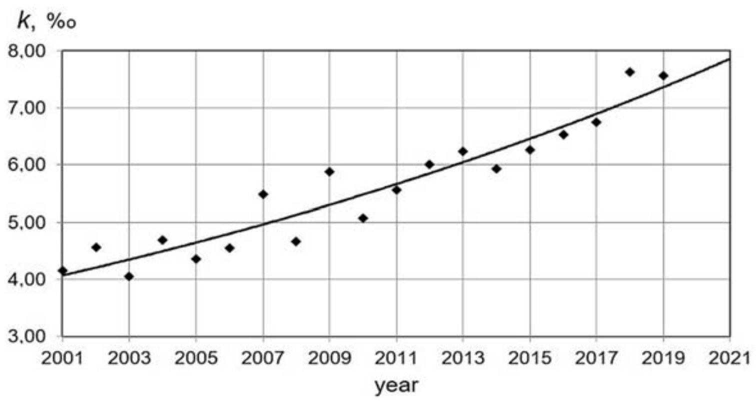

Fig. 1. The level of interest in the metrological self-check k - the share of publications in the field of "measurement", which contain the term "metrological self-check" or words close to it in meaning (as of March 13, 2021).

The same trend has been confirmed by the analysis of Scopus data. The proportions of publications dealing with measurements in special fields and those related to measurements in all fields were calculated. In 2001-2019, this proportion increased by 1.7 times in what concerns measurements in education, twice in the case of sociology, by 2.3 for zoology, and by 5.5 for psychology.

It is logical that that exactly at this time, new concepts related to the wide use of expert judgements, provision of their comparability and compatibility as well as active application of artificial intelligence in measurements have emerged in measurement science. Apparently, it is artificial intelligence together with metrological self-check and virtual tests that eventually leads to

- Mass implementation of automatic diagnostic methods in clinical medicine,
- Wide application of measurements in humanities.

However, even in these cases, the development of new measurement methods and ways for provision of trustworthiness will take place with the delay related to the Kuhn's law. We can only hope that in the new epoch, the time of delay will become shorter due to the increase in the pace of technology development.

4. Artificial Intelligence and Provision of Measurement Trustworthiness

Industry 4.0 has just begun, but the pace of technological development is such that we can already foresee the contours of its completion and start of the next stage (Industry 5.0).

A key feature of artificial intelligence is adaptability, i.e., the ability to adjust to changing conditions.

Mass production will become customized. The role of artificial intelligence will increase significantly, while human involvement in production processes will decrease and, in some cases, be reduced to nothing. Cyber-physical cognitive systems, including robots, will be widely spread. They will often use procedures that are characteristic of intellectual activities, such as image recognition, analysis of trends and their consequences, prediction, decision-making, etc.

At present, many types of sensors and other MIs are produced which measurement range can be adjusted. However, there have emerged the first sensors with an embedded neural network being capable of searching and selecting optimal parameters that correspond to the input signals and influence quantities.

If they are provided with the metrological self-check function, they can be called intelligent, because according to GOST [19, 20], an intelligent sensor / intelligent MMS is an adaptive sensor / adaptive measuring system, with the function of metrological self-check. In considering this definition, to take into account is necessary that the intelligence can be of different level.

The intelligent sensor, as a rule, should have a digital output and provide transmission of information on a metrological failure occurred.

To increase calibration / verification interval without worsening measurement trustworthiness, self-check methods should be supplemented with automatic metrological correction methods (i.e., methods of compensation for uncertainty changes).

The combination of metrological self-check and self-correction functions brings the implementation of MIs and MMSs realising them closer to sensor systems of mammals (surely, including humans) with advanced intelligence. In fact, this makes the intelligence level of the former ones higher. (The behaviour of people who experience visual or hearing impairment, but do not have a possibility to use glasses or hearing aid, is characteristic. They take possible measures to compensate for the originated defect by increasing the attention to information from other sensory systems that are healthier. Besides, they behave more carefully.)

At the end of Industry 4.0 stage, intelligent sensor with necessary calculation resources will enable not only revealing metrological failure and automatic correcting uncertainty that appeared as a result of influence quantity impact and/or material ageing, but also

- Self-recovering if a single sudden malfunction has occurred in the sensor,
- Self-learning.

Self-recovery means an automatic procedure that weakens the metrological failure consequences, i.e., it is a procedure for fault tolerance provision, while fault tolerance is the ability to keep metrological characteristics within permissible limits in case of a single defect.

Self-learning implies the ability to automatically optimise parameters and operation algorithms. Its basis is the dynamics analysis of the events taking place. One of the important purposes of self-learning is developing the reaction to unexpected events.

In a near future, intelligent MMS will include

- Intelligent sensors,
- Several sensors that measure the same quantity and are located at a distance, one of them being more accurate and reliable than the others (direct metrological self-check at the level of MMS),
- Sensors that measure various quantities the relation between these quantities being known with a required accuracy (metrological diagnostic self-check at the level of MMS).

Accordingly, besides revealing metrological failure in one or several measuring channels, intelligent MMS will be able (like in case of intelligent sensors) to carry out automatic correction of uncertainty, self-recovery, and self-learning.

At the stage of Industry 5.0, new ACSs will have the capability for self-learning to parry unexpected events (so called, "black swans"). Given the likelihood of robot "communicating" with each other and with humans, including situations not foreseen by technological instructions, ethical constraints must be built into the robots' artificial intelligence. This aspect should also be taken into account in the formation of self-correction and self-recovery algorithms.

If an intelligent sensor or intelligent MMS is provided with the self-learning capability, a corresponding built-in neural network should be able to be checked, i.e., should be able to reproduce algorithms being realized, including those related to occurrence of unexpected situations. Ideally, the neural network will automatically check whether the solutions made as a result of self-learning correspond to specified limitations.

5. Conclusions

The analysis of tendencies in development of methods and means for providing measurement trustworthiness has been fulfilled. Its results demonstrate that for traditional types of measurements, organisation of the metrological self-check based on the available or artificially introduced redundancy is the most perspective way. In new MIs and MMSs, the metrological self-check should preferably be supplemented with the self-correction of growing measurement uncertainty.

Requirements for terminology, methods as well as the level of metrological self-check and self-correction should be reflected in a set of international standards. The conformity of the realised level to the requirements of the standard should be substantiated in MI or MMS documentation.

Virtual tests have shown to be effective, but there exists a need to systematise the experience gained and issue standards in this field to make the results more evident.

Soft measurement methods and corresponding instruments will become widespread both in the near and more distant future. To ensure trustworthiness of their results, methods for diminishing the subjectivity role in expert evaluations should be developed and included in international standards.

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The Integration of Artificial Intelligence and Measurement Science Methods by the Regularizing Bayesian Approach

Svetlana V. PROKOPCHINA
Financial University under the Government of the Russian Federation,
49 Leningradsky Prospekt, 125993, Moscow, Russia
E-mail: svprokopchina@mail.ru

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Abstract: This article substantiates the need for deep integration in the form of convolution of artificial intelligence methods and measurement theory at all levels of information acquisition and processing to improve the efficiency, stability, consistency, transparency, traceability and quality control of measurement and neural network solutions, intellectualization of data transmission and storage systems (IIoT), and the construction of highly efficient cyberphysical systems.

The paper considers the approach and methodological principles of creating a new type of neural networks, called Bayesian measurement networks. The concept and formalization of a new type of Bayesian neurons implementing Bayesian convolution based on the regularizing Bayesian approach is given. Three types of Bayesian neurons that implement the convolution of the values of quantitative and qualitative features are considered. An architectural scheme and metrological justification of BIN solutions, a platform for rapid development of applied BIN solutions, are proposed. Examples of solutions to applied problems based on BIN are given.

The concept is given and a practical example of an intelligent industrial IoT is given. The expediency and experience of using BITS and cognitive measurements for the construction of CPSS are noted.

Keywords: Artificial intelligence, Measurement theory, Neural network, Regularizing Bayesian approach, Industrial internet of things.

1. Introduction

The development of technologies in the modern information sphere clearly shows the special relevance of the development of principles for the integration of artificial Intelligence (AI) and Measurement Science (MS) methods. On the one hand, artificial intelligence methods, based on experimental information, have a need for sufficient amounts of good-quality data. The quality of the resulting solutions directly depends on the quality of the data. On the other hand, in order to successfully and fully solve applied problems, the measurement results must be interpreted, integrated and processed based on artificial intelligence methods.

The main requirements for both types of systems from international standards (for example, the ISO series) and users are: accuracy and reliability of the resulting solutions, traceability of the processes of obtaining solutions (traceability), (accountability, uniformity of measurements, tracking); transparency of technologies and algorithms for obtaining solutions (transparentability); interpretability of solutions (explainability), which are practically not performed in modern AI systems, in particular, in developments based on neural network technologies. In this aspect, measurement technologies are a good example, in which, as a rule, the first two or three requirements are met.

Until now, so-called integrated systems have combined measurement subsystems with processing subsystems purely "mechanically" in their architecture. This led to the almost autonomous existence of the measurement and computing subsystems in the information media environment. There are both theoretical and practical reasons for this. But to solve applied problems with the implementation of these requirements, it is necessary to coordinate the functioning of AI and MS technologies at each stage of information processing. It is important to "teach" measurement technologies to use information in the form of knowledge, and AI technologies to metrologically certify the resulting solutions, especially in the form of knowledge.

2. Principles of "Convolutional" Connection of AI and MS Technologies

The most significant new principle of integration is the principle of convolutional connection of AI and MS technologies, when the properties and functionality of these systems, interacting in the process of solving an applied problem, provide each other with additional information processing capabilities that are not inherent to them separately. For example, measurement technologies-the possibility of using information in the form of knowledge, extensive opportunities for cognitive methods of interpreting measurement results. Methods of artificial intelligence - the possibility of metrological justification of solutions, management of the synthesis of technologies and ensuring the required quality of the resulting solutions. The transition to a convolutional connection of AI and MS systems provides powerful incentives to implement the principles of Industry 5.0.

The distinctive characteristics of Industry 5.0 from Industry 4.0 in terms of information processing methodology are: personalization of information processing; customization of information processing services; availability of explanatory capabilities; flexibility of software models and structures; self-learning and self-development of application and system software; ensuring high reliability and quality of the resulting solutions; strengthening the cognitive capabilities of software.

Thus, overall, the new principles of Industry 5.0 is directed to methods and systems of information processing on the full intellectualization application and system software (paragraphs 1 to 5, 7) and metrological support decisions (paragraph 6).

How relevant is the issue of quality assessment of the applications of artificial intelligence, its measurement rationale is evidenced by the fact that the international Institute of standards currently offered version of the standard series ISO to control the efficiency and quality of solutions to the artificial intelligence methods.

The intellectualization of data acquisition processes by measuring systems that is, measuring processes, has been relevant since the early 90s of the last century. The first work in the formation of this direction was the work of D. Hofmann and M. Karaya [1]. This was followed in 1986 by the IMEKO Congress, in which a number of applied works devoted to this area of measurement theory appeared. However, all of them were of a very private applied nature and had no theoretical justification. In the 90s, the direction continued to develop in the works of D. Hofmann and L. Finkelstein [1, 2].

In their work, the main focus was the applied problem of self-calibration of measuring systems. For this purpose, some a priori and obtained in the course of measurement assessments and expert knowledge were used. But such additional modules were built in separately, as additional subsystems, and did not participate in the measurement process.

Thus, these were works aimed at the joint but autonomous application of artificial intelligence methods.

To implement the real integration of artificial intelligence methods and measurement theory, it is necessary to use them together in the measurement and information processing processes themselves.

This approach was proposed in the early 90s of the last century in the works [3, 4]. It is called the regularizing Bayesian approach.

The basis for obtaining solutions optimal by the average risk criterion in such technologies is the Bayesian convolution according to the modified Bayesian formula [3]. Convolution is implemented on special scales called conjugate scales with dynamic constraints [9, 22].

This name is due to the structure of the scale, which consists of numerical and linguistic scales, interfaced by their carriers. Such scales allow you to process both numerical and measurement information, as well as information in the form of knowledge. An example of such a scale is shown in Fig. 1.

Information from the instruments is sent to the numerical scale, and from experts or other sources of knowledge to the linguistic scale. For the joint processing of all types of information on the scale, both methods of measurement theory and methods of artificial intelligence, in particular methods of the theory of fuzzy sets and linguistic variables, are used. On the linguistic part of the scale, algorithms for rationing and checking by criteria can be implemented.

In accordance with this, we can call this method of integrating artificial intelligence methods and measurement theory "convolutional", which provides a deep integration of these methods.

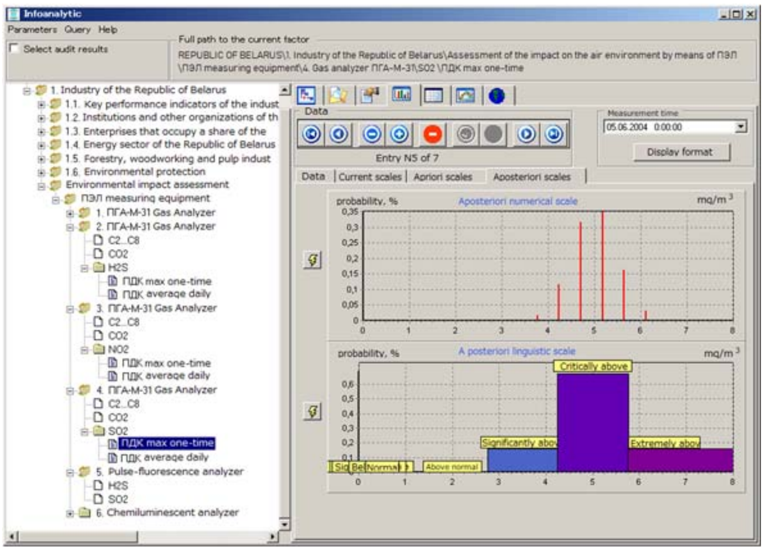

Fig. 1. The conjugate scale of the SDC type used to implement Bayesian convolution.

2.1. Measuring Scales of Quantitative Measurements

Deep integration of artificial intelligence methods and measurement theory is implemented at the lowest levels of obtaining and primary processing of non-qualitative information.

Typification and classification of measurement scales can be carried out on the basis of several main features: objective and subjective measurements and scales; quantitative and non-quantitative measurements and scales.

Quantitative scales are divided into five main types: nominal scales; ordinal scales; interval scales; ratio scales; and absolute scales.

The following classification system for non-quantitative (non-numeric) scales is proposed.

Non-quantitative scales can be divided into sensitive and cognitive scales. The first type of scales is associated with the measurement of emotional properties, sensations, and sensory perceptions; the second-with the representation of knowledge, experience, and skills of subjects and society as a whole, declarative attitudes, norms, and rules in measuring processes.

Sensitive scales are divided into: scales of maxims (sensations); intuitive.

Sensation scales are divided into: sound scales; visual scales; organoleptic (aromatic) scales; tactile scales; emotion scales.

Cognitive scales are divided into: descriptive; predictive; prescriptive scales, reflecting the available knowledge and experience of the subjects, the predictive process, as well as the predictive process with explanations.

All these scales are based on the gradation of the manifestation of properties. For their construction, the concept of an ordinal universal scale is used, for which the reference points are linguistic variables that reflect this gradation of properties.

To measure complex integral properties, we use emergent scales, which allow us to measure the emergent properties of complex objects based on measurements of simple properties.

Criterion conjugate scales. On linguistic scales, you can build criteria scales of a multi-tiered structure. The concept and technologies for creating such scales are proposed and implemented in applied problems within the framework of the regularizing Bayesian approach methodology.

Criteria scales can be objective when they are created on the basis of standards, regulations, and technical guidelines.

They can also be fiducial (subjective), when they are based on norms and principles of a subjective type.

The criteria scales in the BIT methodology are interfaced with the main linguistic SDC for multi-criteria scaling. In this case, together with the measurement process, a multi-criteria audit of the measured characteristics is carried out.

The measurement results on such scales are fuzzy alternative estimates with a full metrological justification of the BIT scales.

Integral (emergent) scales for measuring the emergent properties of complex objects and systems. This type of scale is designed to measure the integral properties of complex objects. The measurement method contains the functional possibility of implementing convolution (convolution) of intermediate measurements of simple properties included in the integral property.

Such scales are used to measure indexes, hierarchical indicators, integral characteristics, and indicators.

Such scales provide interpretability and explanation of the resulting solutions.

Examples of implementing the principles of convolutional integration of AI and MS methods can be Bayesian measurement networks and systems of the intelligent industrial Internet of Things (IIoT) based on RBA and BIT, given in the article below.

3. The Concept of a Bayesian Measurement Neural Network

In [12], the concept, structure, theoretical justification, and applied examples of using a Bayesian measurement neural network are proposed.

The traditionally noted disadvantages of neural networks include the impossibility of semantic interpretation of the received solutions, managing the network operation, and obtaining intermediate solutions. In addition, the quality of input information and its metrological specifics are not taken into account, and therefore the quality of output solutions is not determined.

These shortcomings can be successfully overcome when creating a neural network structure based on the methodology and technologies of the regularizing Bayesian approach (RBA).

It is worth noting that the RBA methodology is developed on the basis of the principles of the theory of pattern recognition and therefore can be reasonably used to build neural networks.

3.1. Methodological Foundations and Principles of Creating Bayesian Measurement Neural Networks

The regularizing Bayesian approach [3, 4] has become one of the successful examples of platform solutions to the problems of modeling and creating developing information technologies, as well as monitoring, auditing and management in conditions of uncertainty.

The modern concept of a complex object in the framework of RBA based on models with dynamic constraints (MDC) involves the construction of a specific model in the process of controlling the system of a complex object or the behavior of an object in a difficult predictive situation and allows for the possibility of changing both the composition of the object properties that form the MDC and their relationships, and the systems themselves for representing properties and relationships.

The results of the solutions are presented as benchmarks of scales $\{h_{kt}\}$ with changing properties according to the incoming information ($\{h_{kt}\} \in H_{KT}; k = 1, K; t = 1, T$). Together, these interconnected scales are a hyperscale (hypercube), which implements a model of the object and its functioning environment in the form of an MDC.

When creating neural networks based on RBA, by analogy with the considered architecture of the analytical neural network, it can be noted that, in fact, the hypercube implements the structure of a convolutional deep learning neural network of a hierarchical type. The convolution is based on a modified Bayesian formula.

All five types of hybrid system layers are present in the Bayesian convolutional network architecture. However, the number of convolutional layers in Bayesian networks is much higher, which provides deep network learning.

The first layer implements configuration (network training), which determines the types of probability density for numerical data and the types of membership functions for linguistic variables, as well as the MDC, the hierarchy of which determines the structure and number of convolutional layers of the network.

The second layer performs the function of fuzzification of variables and metrological justification of decisions based on the following dependence:

$$\{h_{kt}|\{Mx\}_{kt}\} = \{\mathrm{argmin}\, C[\varphi_{it}(x_{it}|y_{it})]\}, \qquad (1)$$

where $\{h_{kt}|\{Mx\}_{kt}\}$ is the fuzzified value of the input variable with the complexes of metrological characteristics of accuracy, reliability, and reliability for each component of the fuzzy set;

C is the optimization criterion in the form of the average Bayesian risk of the solution;

φ_{it} is the Bayesian fuzzification function;

$x_{it}|y_{it}$ is the set of data obtained under y_{it} conditions, including a set of a priori information, restrictions, and metrological requirements.

The chain of constant metrological support for each stage of the implementation of the network algorithm allows us to reasonably define this type of neural network as a *measuring neural network*. And since a modified Bayesian rule (3) is used to implement convolution, such a network can be called a Bayesian *measurement neural network* (BIN) of a hierarchical type with deep learning.

With this architecture, convolutional layers can be represented as feature convolution layers, which allows you to interpret the decisions of each layer in relation to their semantic content.

When two and many features are convoluted, each neuron of such a network is activated on its convolutional layer by an optimizing Bayesian function of the minimum average risk of a C solution of the form:

$$\{h_{kt}|\{Mx\}_{kt}\} = \\ = \{\mathrm{argmin}\, C[\varphi_{jt}(x_{it}|y_{it}; x_{i+1t}|y_{i+1t})]\}, \qquad (1)$$

where $h_{kt} \in H_{KT}, k = 1, K; t = 1, T$;

$\boldsymbol{\varphi_{jt}}$ is the Bayesian convolutional function; $\boldsymbol{\varphi_{jt} \in \Phi_{JT}; j = 1, j}$;

$x_{it} \in X_{IjT}; (i = 1, I)$ are the sets of values of numerical and linguistic variables that reflect the properties of features;

$y_{it} \in Y_{IjT}; (i = 1, I)$ are the conditions for obtaining data and implementing convolution algorithms;

$Y_{IjT} = \{A_{IJT}\}$ is the set of a priori information;

O_{IJT} is the multiple constraints;

M_{IJT} is the set of metrological requirements.

The Bayesian convolution formula has the following form:

$$P(h_k|\ x_i|\ Y_i) = \frac{P(h_k|Y_{i-1})l(x_i|h_k|Y_i)}{\sum_{j=1}^{K} P(h_j|Y_{i-1})l(x_i|h_j|Y_i)}. \quad (3)$$

In the process of such convolution, the probabilities of rappers of the feature scales are transformed, information about which enters the system in the form of input data streams and knowledge about the features.

Let's call this type of neuron a *Bayesian neuron*.

Let us consider in more detail the implementation of the Bayesian convolution to explain the previously given definitions and the above reasoning.

The scale of the SDC type can change its properties and structure (carrier, reference points, composition of permissible ratios, etc.) according to the change in the structure of the MDC. That is why it is called a scale with dynamic constraints (SDC). Its appearance is shown in Fig. 1.

The SDC scale for measuring the properties of a one – dimensional indicator is a two-dimensional scale, along one of the axes of which the values of the indicator are plotted in numerical or linguistic forms, and on the other-the degree of confidence (confidence, possibility) of the result. Therefore, it is called conjugate SDC.

The synthesis of RBA information technologies is based on the principle of unity of measurements, which allows to coordinate the inputs and outputs of individual scales and transform them in accordance with the functional content of the information technology and compliance with the metrological requirements for information system solutions. At the same time, a single information space is formed with a topology determined by metrological requirements and characteristics of information flows according to the R methodology [20]. For this purpose, in parallel with the computational process, the process of metrological support of each solution is implemented in the form of indicators of accuracy, reliability, reliability, entropy and risk. These indicators are combined into complexes of metrological characteristics. Metrological complexes determine the quality of solutions by many indicators, both for solutions in numerical form and for solutions in linguistic form in the form of knowledge. The theoretical justification of the metrology of data and knowledge is given in [11].

The solution obtained on the basis of Bayesian convolutions is a series of alternative feature estimates with corresponding complexes of metrological characteristics and is a regularized Bayesian estimate, the properties of which are considered in [3].

Explanations of the functionality of the elements of this scheme are given below.

In the BIN, according to the neuron formula, three types of convolutions are implemented.

1. Convolution of a priori and a posteriori values of numerical or linguistic variables (Bayesian neuron type 1).

2. Convolution of values of numerical and linguistic variables (Bayesian neuron of the 2nd type).

3. Convolution of the integrated values of various features (Bayesian neuron of the 3rd type).

As already noted, the parallel branch of each stage on each convolutional layer implements full metrological support for solutions.

The scheme of convolution of the 3rd type is shown in Fig. 2, i.e., the structure of the implementation of a neural network on a convolutional layer with the 3rd type of Bayesian neurons is reflected when the values of two different variables are convoluted.

This allows you to create a single technology with the ability to manage the quality of the resulting solutions.

The scheme for implementing Bayesian convolution in the BIN system is shown in Fig. 4.

With repeated implementation of convolution, there is a sharp decrease in the dimension of the feature space, which allows processing a significant number of data streams at high speed.

3.2. Software Implementation of BIN

The 'Infoanalytic' platform [18], which is essentially a BIN, is built on these principles. Unlike neural networks in application systems built on its basis, all convolutional layers are easily viewed in the user interface and interpreted using cognitive graphics.

For each feature, as solutions, you can get comprehensive information, dynamic characteristics, trends, assessments of situations and recommendations for their adjustment in accordance with the specified norms and rules. Examples of applied solutions with explanations for heat power engineering are illustrated in Fig. 3, 5.

So, in the example shown in Fig. 1 on the left, a conceptual model of the measurement object (the state of the air environment) is presented in the form of a tree of factors, in fact, representing a scale of the nominal type. This model is conditionally adequate to the real object within the framework of the available and used information, requirements and restrictions.

For the integral indicator, a new two-dimensional scale of this type is formed:

$$\mathbf{h_t^{integral}|\{MX\}_t^{integral}} = \mathbf{h_{It}|\{MX\}_{It} * h_{2t}|\{MX\}_{2t} * \ldots * h_{kt}|\{MX\}_{kt}}\,, \quad (2)$$

where $h_t^{integral}|\{MX\}_t^{integral}$ is the set of alternative solutions of an integral indicator with complexes of metrological characteristics containing indicators of accuracy, reliability and reliability of solutions $h^{integral}$ belonging to a dynamic compact of solutions H, *is a symbol of generalization of elements, systems $\{h_{kt}|\{MX\}_{kt}\}$ is a set of alternative solutions of one-dimensional indicators with complexes of metrological characteristics containing indicators of accuracy, reliability and reliability of solutions h_t belonging to a dynamic compact of solutions H.

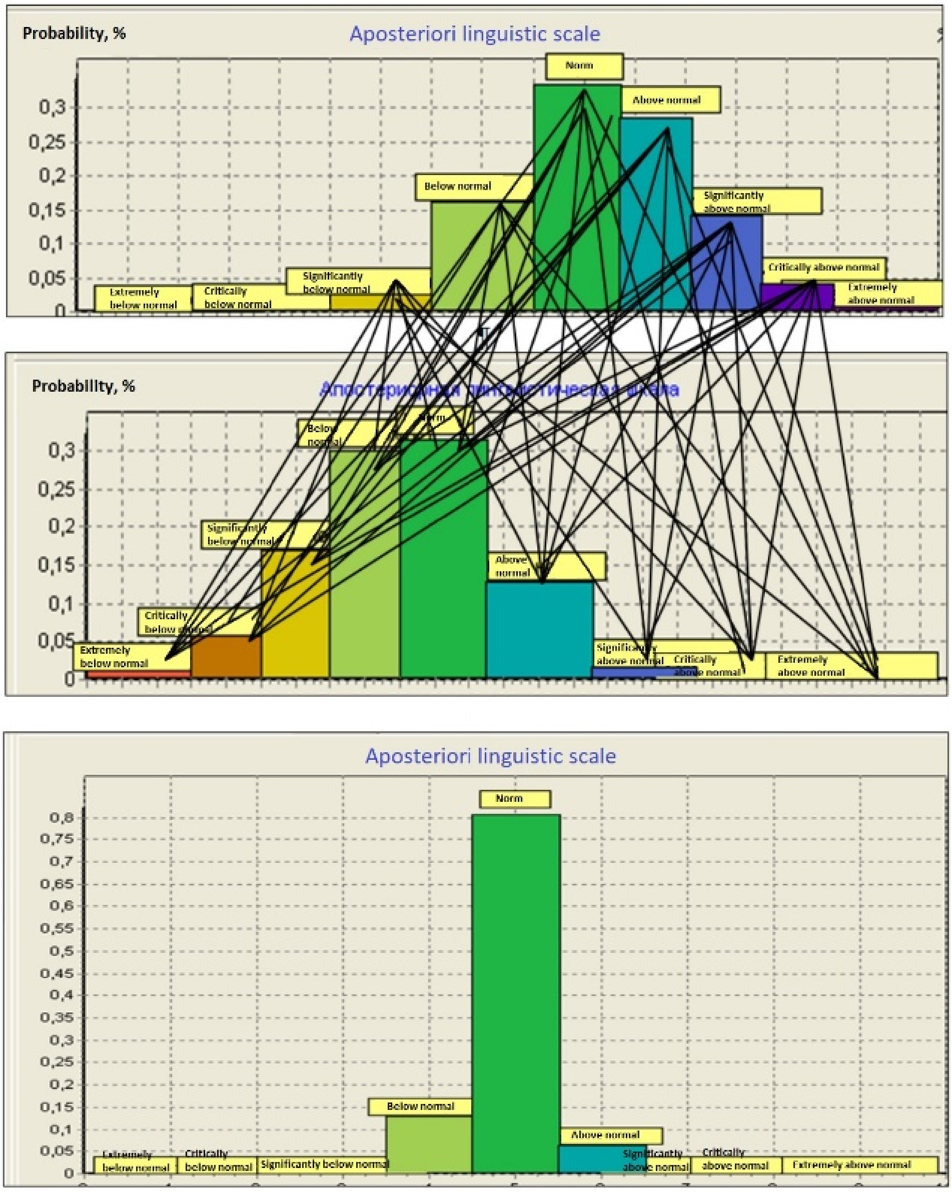

Fig. 2. Illustration of Bayesian convolution principles for the BIN scheme.

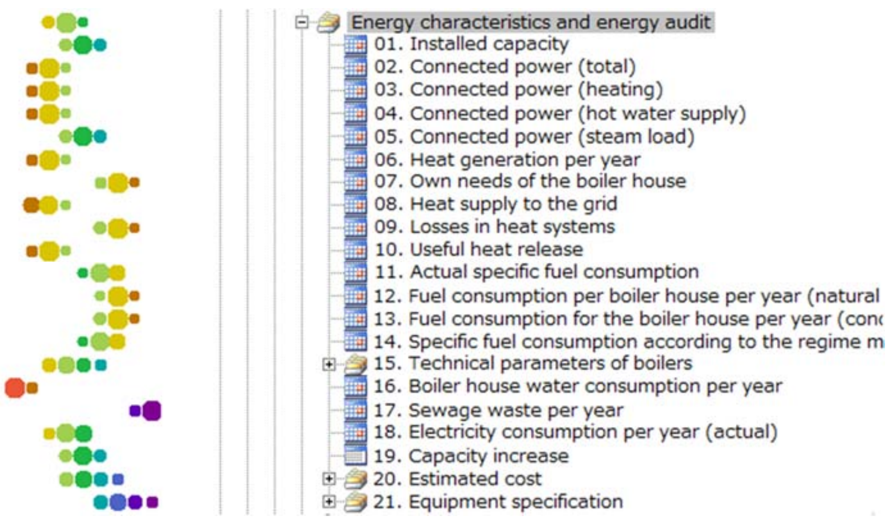

Fig. 3. Convolution of indicators of heat-generating systems with cognitive interpretation of solutions.

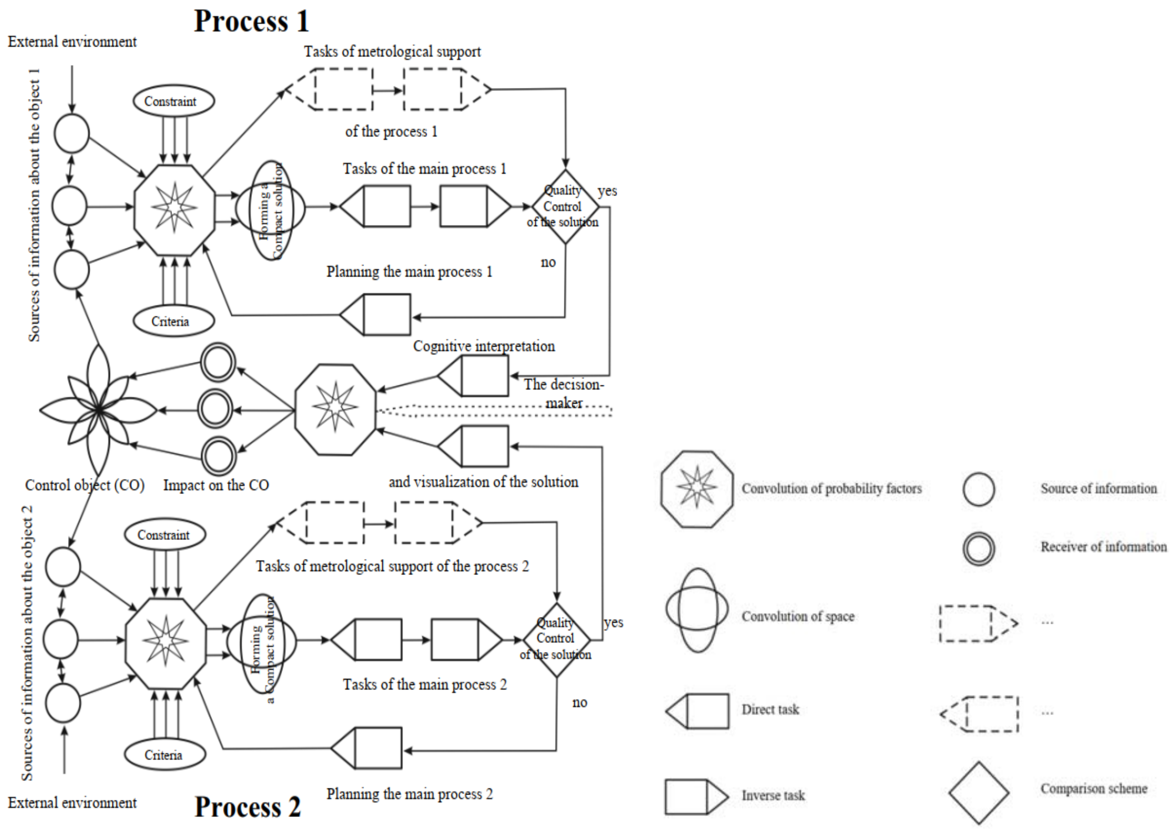

Fig. 4. A scheme for implementing convolution with Bayesian neurons of type 3.

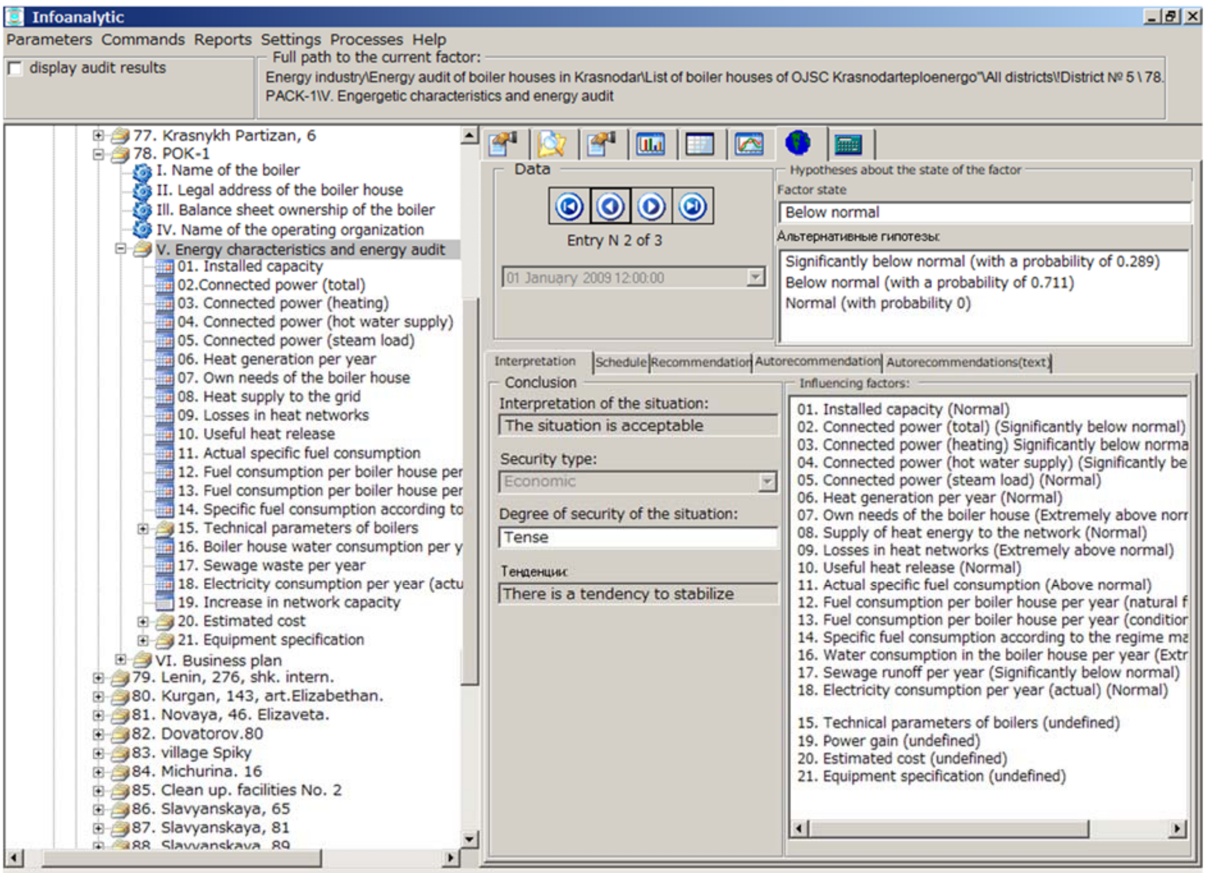

Fig. 5. Convolution of signs of the state of the energy-generating system with explanations.

Thus, the SDC structure is developed according to the MDC structure, and the model and the nominal scale of factors representing it in the Infoanalytic environment are continuously developed.

4. Metrological Characteristics of the Quality of BIT Solutions

As it is noted about many scientific works, the most important issue of intellectualization is the question of the truth of the knowledge and solutions obtained. In Bayesian intelligent technologies, every decision, every model, and every management recommendation has decision confidence indicators that characterize the conditional truth of the decision in terms of available constraints, a priori information, and criteria requirements. In addition, the solution is accompanied by indicators of accuracy, reliability (in the form of estimates of error levels of the 1st and 2nd kind), indicators of the information utility of the solution, the risk of solutions, entropy characteristics, which are combined into complexes of metrological characteristics that ensure the stability and convergence of the obtained solutions under uncertainty. The rationale for the choice of indicators of metrological complexes is given in [11] Such complexes are interconnected for individual solutions and together form a system of metrological support, which allows the synthesis of bits in accordance with the required metrological characteristics. This determines the uniqueness of bits among all similar technologies. The solution obtained on the basis of Bayesian intelligent technologies is a series of alternative property estimates with corresponding sets of metrological characteristics.

However, it should be noted that all estimates of metrological indicators are conditional within the framework of the available a priori information and restrictions.

Therefore, the absolute truth of solutions is unattainable because of the fundamental unknowability of absolutely all the properties, characteristics and relationships of complex systems.

The introduction of a system of scales in BIT allows you to control and control the conditional accuracy of solutions, their reliability and reliability in solving the problem of system synthesis, which is considered in a number of works by the author [3, 9, 11].

5. IIIOT – Intelligent Industrial Internet of Things

Currently, the IIoT direction is actively developing. Understanding the need to pre-process measurement data before transmitting it through communication channels led to the formation of the direction of peripheral computing and the concept of DATALAKE.

From ETL structures, the transition is made to some ground-based local data storage (DATALAKE), focused on the specifics and mode of operation of applied information systems. At the same time, there is a clear trend towards the inclusion of data pre-processing modules for the organization of peripheral computing.

To implement this trend, it is proposed to use Bayesian intelligent technologies and neural network application systems based on them. Such systems will make it possible to significantly reduce the dimension of the stored data in the framework of solving specific application tasks, while fully preserving their information content. In addition, such systems can be used to integrate data and knowledge in the field of information collection, transmitting ready-made assessments of processes and situations, as well as local management decisions, over the network.

An example of such systems is the monitoring systems of water management, power generation, control organizations and services [16, 19].

The distinctive characteristics of intelligent IIoT from traditional IIoT structures are the presence of intelligent data processing systems in them, in particular, in the example given, the presence of a Bayesian measuring neural network for convolving data received from devices and obtaining solutions in the form of assessments of situations with explanations of the reasons and factors for their formation, as well as with recommendations for correcting the situation on the ground. In this way, the IIoT structure is arranged in all sections of the water supply network. The integrated information is then transmitted by IIIoT to the central processing unit for information received from other types of sources.

One example is a system that is a hierarchically organized, geographically distributed environment for monitoring the state of water management networks and supporting water management decision-making in conditions of significant amounts of data, diverse information and uncertain situations.

The system architecture is shown in Fig. 6.

The system consists of the following main blocks:

1. The central block of intelligent information processing based on a neural network of the BIN type with a library of mathematical modeling and development of scales of the SHDO type (G1)
2. Analytical neural network for generating scenarios and recommendations; (G2)
3. A unit of measuring instruments with converters and controllers and with pre-processing of measurements; (G3)
4. Thermal image processing neural network; (G4)
5. System interface for analytical neural network; (G5)
6. System interface for image neural network; (G6)
7. User interface; (G7)
8. Server blocks. (G8)
9. WEB servers and services
10. A block (local) IIIoT with a built-in neural network of the BIN type.

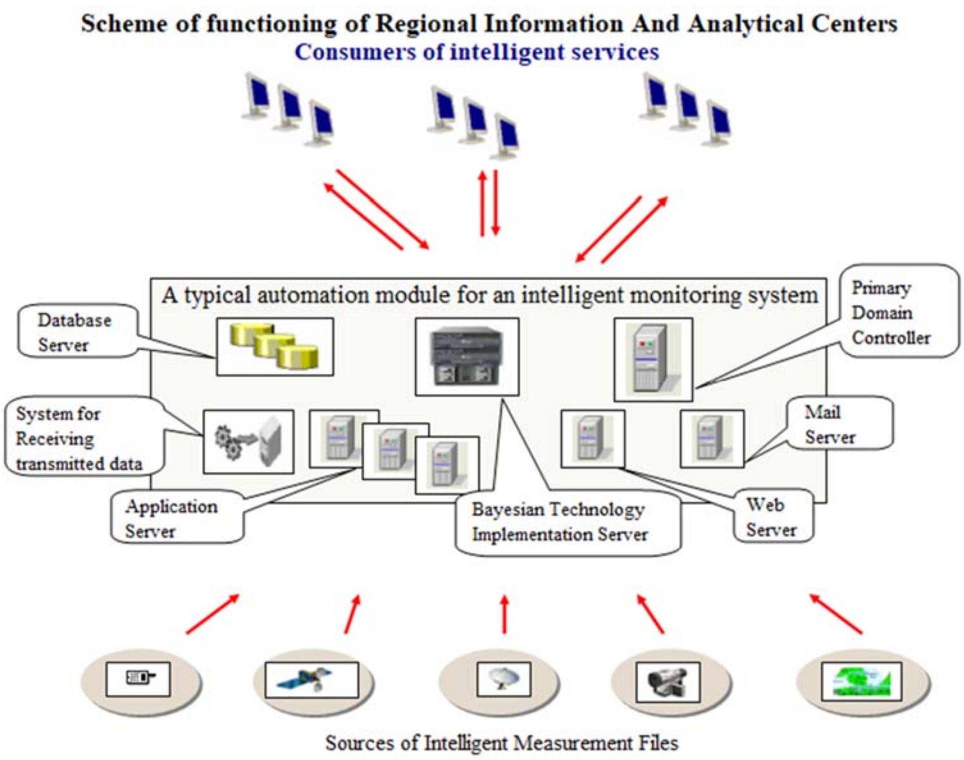

Fig. 6. Architecture of the intelligent industrial Internet of Things based on a typical module of the intelligent DATALAKE.

Integration with the specified software blocks takes place according to the selected data exchange protocols in the on-line and of-line modes.

The information model is focused on the object of monitoring, in particular, the section of the water supply network. (Go).

The object is a node of a section of a heating main. The parameters of the heating main unit must be controlled by the measuring unit (Gm). A measurement unit is a measurement system that receives measurement information, logs it, and transmits it to a top-level information system. Controlled parameters: water flow-two flow meters Gd; pressure-two pressure sensors Gp; temperature-two temperature sensors Gt; humidity sensor Gg.

The information model of the measuring unit has the following form:

$$\mathrm{Gm} = \mathrm{Gd} * \mathrm{Gp} * \mathrm{Gt} * \mathrm{Gg},$$

where * is the convolution symbol of the information according to the modified Bayes formula.

In addition to the numerical measurement information specified above, a series of Gi images obtained by means of a thermal imager is used as an information stream, identifying the heating of the surface of water supply pipes at their surface locations.

With this in mind, the information model can be presented in an expanded form: $\mathbf{Gm1} = \mathbf{Gm} * \mathbf{Gi}$**.**

Another important information flow is the recommendations and scenarios coming from the analytical neural network (Gn).

Then the information model of the system can be represented as: $\mathbf{Gm2} = \mathbf{Gm1} * \mathbf{Gn}$**.**

The mathematical basis of this project and the system of monitoring and management decision-making are the regularizing Bayesian approach (RBP) and Bayesian intelligent technologies, the basic ones of which are Bayesian intelligent measurements (BII).

Since BII-type measurements are made under conditions of significant uncertainty regarding the exact knowledge about the model of the measurement object, measurement conditions, and measuring instruments, which can be either instrument-based or expert knowledge, which introduces instability in the measurement process and the resulting solutions, it is necessary to implement measurements within a single regularized solution space.

As a model object, in particular, the reference points of measurement scales, can be not only numerical values, but also functions, situations, images of objects, scenarios, which together represent a conditionally complete group of events reflected by the reference points of the measurement scale carrier. Such scales can be parametric, functional, or system scales with their corresponding benchmarks in the form of parameter values, model functions, and systems.

The problem of measurement in conditions of uncertainty is set as the problem of restoring values or metrological classification of images, which determines the need to ensure the stability of its solutions. Therefore, in complex measurement situations, the representation of the measurement problem is used as a set of inverse problems of restoring values, states, and situations from the received information.

The measurement technique can be a complex information technology.

For each measurement solution, metrological justification of models, algorithms, and solutions is provided in the form of indicators of accuracy, reliability, reliability, risk, and information content of solutions.

5.1. Generalized BII Equation

For the purpose of methodological formalization, a generalized measurement solution is obtained for all types of measurements, including BII and MI measurements. The measurement equations for all types of classical measurements, as shown in [15], are special cases of this generalized equation.

So, for Bayesian intelligent measurement, the measurement equation is written as follows:

$$\left\{\mathrm{h}_{\mathrm{kt}}^{(\mathrm{Q})}\middle|\{\mathrm{MX}\}_{\mathrm{kt}}^{(\mathrm{Q})}\right\}|\left(\mathrm{Y}_{\mathrm{t}}^{(\mathrm{O})} * \mathrm{Y}_{\mathrm{t}}^{(\mathrm{OE})} * \mathrm{G}_{\mathrm{t}}^{(\mathrm{OE})}\right) = \{\mathrm{argexstr}\ \mathrm{C}^{(\mathrm{B})}[\varphi_{\mathrm{j}}\left(\mathrm{f}_{\mathrm{it}}\{\mathrm{X}_{\mathrm{it}}\}|\left(\mathrm{Y}_{\mathrm{t}}^{(\mathrm{Q})}\right)\right) * * \mathrm{Y}_{\mathrm{t}}^{(\mathrm{OE})} * \mathrm{G}_{\mathrm{t}}^{(\mathrm{OE})}]\}, \quad (1)$$

where $\left\{\mathrm{h}_{\mathrm{kt}}^{(\mathrm{Q})}\middle|\{\mathrm{MX}\}_{\mathrm{kt}}^{(\mathrm{Q})}\right\}|\left(\mathrm{Y}_{\mathrm{t}}^{(\mathrm{O})} * \mathrm{Y}_{\mathrm{t}}^{(\mathrm{OE})} * \mathrm{G}_{\mathrm{t}}^{(\mathrm{OE})}\right)$ is the fuzzy solution to the problem under the conditions of $\mathrm{Y}_{\mathrm{t}}^{(\mathrm{O})}$, (determined by a priori information, requirements, restrictions and assumptions) of the functioning of the object; under the conditions of influencing environmental factors $\mathrm{Y}_{\mathrm{t}}^{(\mathrm{OE})}$; in the compacts of the set of properties of the object $\mathrm{G}_{\mathrm{t}}^{(\mathrm{O})}$ and the environment $\mathrm{G}_{\mathrm{t}}^{(\mathrm{OE})}$.

$\{\mathrm{MX}\}_{\mathrm{kt}}^{(\mathrm{Q})}$ is the set of metrological characteristics of solutions containing indicators of accuracy, reliability, reliability, solution risk, entropy, and Fischer information;

$\mathrm{C}^{(\mathrm{B})}$ is the criterion that sets the logic of solving the problem; in Bayesian intelligent technologies, it is the Bayesian criterion of the average risk of solving; in soft dimensions, it is the Zadeh logic; in classical dimensions, it is the Lukasevich logic;

φ_{j} is the Bayesian intelligent technologies that define and implement solution regularization;

f_{it} is the computational or algorithmic technologies used to process the available primary information;

X_{it} is the set of information flows (data and knowledge) used to obtain solutions.

The equation for fuzzy measurements differs in that, in general, it can have non-Bayesian criteria for the output of solutions to C. But its result, as in equation (1), is represented by a list of alternative solutions with different degrees of confidence, which is calculated for any indicator, for example, for evaluating the influencing factors of the external environment, according to the modified Bayes formula [3]:

$$\mathbf{P}\left(\mathbf{h}_{\mathbf{kt}}^{\mathbf{F_t}}\middle|\mathbf{G}_{\mathbf{t}}^{(\mathbf{OE})}\right) = = \frac{\mathbf{P}^{\mathrm{a}}\left(\mathbf{h}_{\mathbf{kt-1}}^{(\mathbf{F_t})}\middle|\mathbf{G}_{\mathbf{t-1}}^{(\mathbf{OE})}\right)\overset{\mathbf{L}}{\circ}\mathbf{P}\left(\mathbf{G}_{\mathbf{t}}^{(\mathbf{OE})}\middle|\mathbf{h}_{\mathbf{kt}}^{(\mathbf{F_t})}\right)}{\sum_{j-1}^{J}\mathbf{P}^{\mathrm{a}}\left(\mathbf{h}_{\mathbf{jt-1}}^{(\mathbf{F_t})}\middle|\mathbf{G}_{\mathbf{t-1}}^{(\mathbf{OE})}\right)\overset{\mathbf{L}}{\circ}\mathbf{P}\left(\mathbf{G}_{\mathbf{t}}^{(\mathbf{OE})}\middle|\mathbf{h}_{\mathbf{jt}}^{(\mathbf{F_t})}\right)} \quad (3)$$

The differences from the measurement equation according to the classical scheme of measuring physical quantities are: the explicit introduction into the equation of the criterion for choosing a measurement solution, information and technological transformations in accordance with the methodology and methodology of measurements, influencing external factors, as well as conditions that formalize the measurement situation.

Among the main differences from the classical methodology for measuring physical quantities are also the following.

Ensuring the development of measurement methods, models, and algorithms depending on changing measurement conditions.

Cognitiveness and interpretability are provided directly in the process of forming a measurement solution.

In the measurement process, it is possible to use, process and convolve both numerical and qualitative, linguistic information

Ensuring the stability of the resulting solutions during integration, identification of system models and their characteristics

Obtaining measurement solutions not only in the form of numerical parameter values as in classical measurements, but also in the form of models, audit decisions, recommendations, assessments, conclusions, and scenarios.

The conditional nature of the obtained solutions, that is, the measurement solutions will be valid only if the experimental conditions are met, namely: within the given compact of solutions, the set constraints, metrological requirements, and the available a priori information.

A mathematical model of the monitored object in the view of the portion of the water distribution network can be represented as a set of properties of a complex system in the form of Go: $\mathbf{Go} = * \mathbf{i} = \mathbf{1}, \mathbf{I}\ \mathbf{Gbi}\ (*\ \mathbf{j} = \mathbf{1}, \mathbf{J}\ \mathbf{Gbiq}),$

where Gbi – a conceptual model of the linear sections of the network I is the number of line sections of the water distribution network; Gbiq models of built-in blocks (wells) on the i-th section of the network, J is the number of wells in the i-th linear part of the network.

The mathematical model for the implementation of the project in the software environment should be supplemented with the system model of the Gs information and measurement complex blocks.

The mathematical model for the implementation of the project in the software environment should be supplemented with the system model of the Gs information and measurement complex blocks.

$$\mathrm{Gs} = \mathrm{G1} * \mathrm{G2} * \mathrm{G3} * \mathrm{G4} * \mathrm{G5} * \mathrm{G6} * \mathrm{G7} * \mathrm{G8} * \mathrm{G9}$$

The generalized model of information processing in the system, taking into account the above dependencies, has the form: $\mathbf{G} = \mathbf{Go} * \mathbf{Gs} * \mathbf{Gm2}$.

Examples of the implementation of such a system are given in [16, 19].

6. Application of the Concepts and Tools of BIN and IIIOT in the Creation of Cyber-Physical (CPS) and Cyber-Physical-Social (CMS) Systems

In general, the concept of CPS is far from new, since its theoretical basis has not yet been developed, which allows us to consider CPS as a fundamentally new object in the field of IT. As often happens, well-known objects are given a new name. In particular, cyber-physical systems are, in fact, well-known systems for monitoring and managing man-made natural complexes, which have been worked with since the 70s.

An important aspect of the functioning of the CPS is the conditions of uncertainty of information and information situations that lead to instability of evaluation and management decisions. Therefore, methods and technologies based on the regularizing approach and BITS have proved to be very effective for creating such systems of various applications.

Many examples of the use of BIN in monitoring and management tasks in natural and man-made complexes are given in the literature [15, 16, 18, 19, 25].

So, since the 90s of the last century, systems for monitoring and supporting management decisions in the energy, industry, ecology, environmental protection and social spheres have been created on the basis of BIT. They weren't called cyberphysical systems, but they were essentially them.

In such intelligent distributed systems based on BITS and BINS, the IIIoT in the locations of the distributed system used intelligent workstations of specialists (IRM) of an applied orientation. A total of 28 types of IRMS were developed.

CPSS are social-oriented cyberphysical CPS systems in which the physical natural environment is considered in conjunction with human communities.

In such systems, it is advisable to use cognitive measurements [10] within the BIN with the inclusion of a person in the CPSS system circuit as a decision-maker, source and receiver of information.

Cognitive measurement is organized by combining experimental information $\{X_{it}\}$ and available data with assessments, knowledge, and solutions $\{X_{it}(st)\}$ of the measuring subject, which was proposed and discussed in detail in [10]. It provides a theoretical justification for the degree of uncertainty and the amount of information value introduced by the subject into the measurement and computing process, and also proves the need to convolve the subject's information with the main information flows coming from technical devices. In these works, the theoretical foundations of the metrology of subjective information are presented. At the same time, a portrait of the subject's competence is drawn up, which is taken into account when processing information.

Based on this, the equation for cognitive measurements is written as:

$$\{\mathbf{h}_{\mathbf{kt}}(\mathbf{Q})|\{\mathbf{MX}\}_{\mathbf{kt}}(\mathbf{Q})\}|\left(\mathbf{Y}_{\mathbf{t}}(\mathbf{O}) * \mathbf{Y}_{\mathbf{t}}(\mathbf{OE}) * \mathbf{G}_{\mathbf{t}}(\mathbf{OE})\right) = \left\{\mathbf{argexstr}\,\mathbf{C}(\mathbf{L})[\,\boldsymbol{\varphi}_{\mathbf{j}}(\mathbf{f}_{\mathbf{it}}\{\mathbf{X}_{\mathbf{it}}\} * \{\mathbf{X}_{\mathbf{it}}(\mathbf{st})\}|(\mathbf{Y}_{\mathbf{t}}(\mathbf{Q})\} * * \mathbf{Y}_{\mathbf{t}}(\mathbf{OE}) * \mathbf{G}_{\mathbf{t}}(\mathbf{OE})]\right\}, \qquad (4)$$

where $\{X_{it}(st)\}$ is the information received from the entities participating in the system.

Based on this equation, cognitive measurement networks are created.

7. Conclusion. Prospects of Integration of BII and BIT Technologies with Modern Information Technologies of Artificial Intelligence and IIOT Systems

DATA Science, BIG DATA, BI, IoT, DSS, DATA Mining, and other systems related to intelligent data processing can be mentioned as promising areas for using the methodology, technologies, and tools of intelligent measurement, as discussed in detail in [12, 15]. The advantages of using intelligent measurements for modern artificial intelligence and measurement technologies can be expressed as follows:

1) In DATA Science systems - for metrological certification of data and knowledge flows, as well as their integration;

2) In IoT systems-for the collection, integration and interpretation of instrumental data for the creation of data lakes with prescriptive analytics, for the development of MES technologies and platforms;

3) In BI-systems - for analytical processing and interpretation of information;

4) In neural networks - for the collection, metrological certification and convolution of data and knowledge in order to attract additional information when compiling a data set and training a neural network;

5) For BIG DATA systems – in order to significantly reduce the dimension of information flows;

6) For systems of mathematical and analytical information processing, in particular for uncertainties and small samples;

7) For digitalization systems – for the collection, intelligent processing of information, the creation of systems for monitoring and managing complex industrial and socio-economic complexes, as well as their sustainable development.

Thus, the main idea of this article is formulated as the need for deep integration in the form of a convolution of artificial intelligence methods and measurement theory at all levels of information acquisition and processing to improve the efficiency, stability, consistency, transparency, traceability and quality control of measurement and neural network solutions, the intellectualization of data transmission and storage systems (IIoT), and the construction of highly efficient cyberphysical systems.

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