Intelligent Polymetric Systems Industrial Applications

Yuriy D. Zhukov[a,b], Oleksii V. Zivenko[a,c]

[a] Admiral Makarov National University of Shipbuilding, Central Avenue 3, Mykolaiv, 54000, Ukraine
[b] "C-Job Mykolaiv" LLC, Shoseina Street 5/1, 54029, Mykolaiv, Ukraine
[c] "AMICO Digital" LLC, Spasska Street 1/7, 54001, Mykolaiv, Ukraine

Abstract

In this article, authors present the latest developments of polymetric sensory systems (PSS) theoretical background and their integration with intelligent industrial robotics and control systems. New results in the axiomatic theory of polymetric measurements development are described. Introduction of the concept of hyper signals of the third genus allowed authors to develop a new set of consequences of the axioms of this theory. The influence of these theoretical developments on further diversification of PSS application in information technologies and embedded smart systems in different industries are analyzed.

Keywords

Polymetric sensory system, smart embedded system, axiomatic theory, hyper signal

1. Introduction and Related Works Review

The concept of the polymetric signal [1], development of the axiomatic theory of polymetric measurement [2], and experience in the application of polymetric sensors for the embedded ship safety control systems [2, 3] engendered strong incentive to apply similar sensing subsystems in intelligent and robotic systems in different industries. Smart decisions are based on the knowledge of the system as well as ambient conditions and influence factors provided with high accuracy by sensors. The sensor serves as the source of information for all subsequent applications and decisions. Sensing subsystems nowadays are practically realized utilizing embedded systems, IoT and appropriate infrastructure. In the world of Instrumentation and process control, a "sensor" is defined as a device that detects changes in physical properties and produces an electrical output in response to that change. Nowadays, the usage of so-called «smart sensors» in industrial applications, their effectiveness and positive impact are undeniable [4, 5]. The «smart sensor» concepts play an important role in Industry 4.0, where «smart sensors» are one of the key points in establishing manufacturing intelligence [6]. Roughly «smart sensor» is a sensor that can perform sensing of a physical property change. It also executes data conversion and digital processing. It can communicate to external devices, do some of self-diagnostics, self-assessment, self-calibration and even has reconfigurable hardware or/and

ICT&ES-2020: Information-Communication Technologies & Embedded Systems, November 12, 2020, Mykolaiv, Ukraine
Yuriy.zhukov@nuos.edu.ua (Y.D. Zhukov); oleksii.zivenko@nuos.edu.ua (O.V. Zivenko)
0000-0002-7454-8007 (Y.D. Zhukov); 0000-0002-1539-8360 (O.V. Zivenko)
© 2020 Copyright for this paper by its authors. Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).
CEUR Workshop Proceedings (CEUR-WS.org)
CEUR-WS.org/Vol-2762/paper8.pdf

software. Such smartness became possible due to sustainable development and integration of computer-based technologies and embedded systems [7].

In contrast to conventional, non-networked sensors, Industry 4.0 sensors deliver more than just measurement data. Their computing power and flexible programmability are essential characteristics for making production processes more flexible, dynamic, and efficient. Intelligent sensory systems of the future should be energy-efficiency because of the focus on autonomy and cost-efficient functionality.

According to [2, 3] the polymetric sensing might be effective road-map of such a development. The polymetric sensor can be defined as a device that detects changes in more than one parameter of physical properties of a controllable object but uses one specially designed sensory element or a set of specially-designed sensors and transducers. Such an approach allows to measure and estimate multiple parameters simultaneously with fewer sensory components. Thus the essential difference between PSS and conventional measurement systems lies in their informational and energy efficiency.

Unlike traditional multi-parameter sensors/systems, e.g. [8, 9, 10], PSS uses one sensor to estimate the full set of required parameters or maximum available number of parameters in uncertain or harsh conditions of measurements. Polymetric sensor (or polymetric sensory system) is designated to give an output for the end-user wider than the conventional multi-parameter measurement system. It is important to note that polymetric sensory systems are designed to reduce hardware complexity (fewer sensors) and at the same time to enlarge the output of information for an end-user and to improve the quality of this information. It also estimates itself the quality of measurements and estimation results. The above advantage may be achieved only by using specially designed sensors, appropriate measuring and processing techniques [11] and corresponding data-based domain models loaded to PSS [2].

Modern control system sensors have evolved from simple transducers of physical quantities to expert systems. Those systems can assess the measures carried out and take the appropriate decisions in complete autonomy using, for example, the concepts of multi-agent systems [12, 13]. It has become widely recognized [14] that the future factory should be a smart facility where design and manufacture are fully integrated into a single engineering process that enables 'right first time' every time production of products to take place. It seems entirely natural for use embedded monitoring or intelligent control systems [15] at such factories to provide an online, suitable and precise assessment of not only the quantity and quality of the produced products but also the technological, economic and ecological efficiency and safety of appropriate processes realized. At the same time, the introduction of the concepts of holonic multi-agent agencies, artificial intelligence and machine learning methods [16, 17, 18] has enormously facilitated the development of intelligent monitoring and control systems in various fields of human activities including different production, transportation and social processes. The idea to integrate sensory PSS with holonic agencies philosophy and methods seemed to be very fruitful. The achievements in applying such concept for building embedded PSS and appropriate synergy were achieved in frames of projects for the processes control at the motor oil production plant, floating docks processes automation, safety control at nuclear power stations, at grain trans-loading, oil-products or LPG terminals, etc.

The classical control scheme is based on the use of information from various sensors or measurement subsystems, user inputs and the use of preprogrammed logic, set points and controllable object model, other algorithms for producing control actions. The control action usually initiated by a programmed logical controller (PLC) or equivalent. Due to the complexity of the hardware, complicated control algorithms, practical expediency, safety-related reasons measurement subsystem and control subsystem are usually separated in hardware (sensors + data acquisition and preparation system + control system). In contra, in the case with PSS, it seems natural to add to the structure of PSS components for operative control based on estimated and predicted object state parameters. This feature can be defined as the next step in the convergence of control and measurement systems. The authors claim that control signals can be the part of an output vector of a PSS and can be defined as a derivative function of the polymetric signal, target function (or setpoints) and preliminary information about the controllable object (object model, data-based model, etc.). Such PSS became a controller and can be implemented for operative control and urgent actions producing (so the control loop can be realized on the bottom level of a controllable process). This feature can be especially useful in safety-related applications and applications where harsh conditions are present, and the signals can't be operatively transmitted, but the urgent action needed.

An example can be easily illustrated based on a control system with wirelessly connected sensors – e.g. the technique described in [10]. Such a system may have possible problems with a wireless network and data transmission (due to electromagnetic disturbances), that lead to the control in uncertain conditions and control algorithms complexity. The usage of PSS in this case with an internal local control loop makes it possible to avoid some emergencies.

Let us use a biological analogue with human or animal reflexes system. PSS may in a similar way percept (sense) the physical properties of an environment (controllable object or process) and save obtained information, produce some conclusions using various loaded models and knowledge (experience or heuristic) about it. Then PSS is capable of reacting (reflexing) accordingly, making control signals for actuators in local control loops if it's needed and transmit the information about it to the upper level.

However, such an optimistic prospect meets in practice particular problems and restrictions. One of the most critical issues relates to quite different axiomatic grounds of metrology theory and control science and somewhat discrepant methods from timing constraints point of view. Thus, we face an actual and urgent need to integrate and combine the theoretical foundations for the above-advanced approaches, as this may be a precondition for generating real benefits in the field.

2. Proposed technique

The latest results of the development of the axiomatic theory of polymetric measurements engendered intensive diversification of application of polymetric sensors in different new fields and further improvement of already industrialized monitoring and control systems. It is based on the use of latest achievements in metrology, Artificial Intelligence or AI, Holonic Agencies theory, Big Data and Machine Learning instruments, which engendered its development.

2.1. Basics of the axiomatic theory of polymetric measurements

In classical industrial metrology, it is presupposed that for practical measurement processes it is necessary to have the set of different instruments with various sensor transformation principles, sensors construction, and time constants. Furthermore, each device has a custom-made uniform scale for the assessment of the actual value of the object-specific measure of its characteristic under control.

Polymetric measurement, in general, is the process of getting simultaneous assessments of a set of object physical quantities (more than two) with different time constants using one special measuring transformer (a polymetric sensor).

In general, polymetric measurements theory is based on the following axioms (PMTA):

- Axiom 1^P. Tuple $Z =< z_1 z_2 ... z_i ... z_n >$ of integer numbers is brought in correspondence with every result of any measuring experiment.
- Axiom 2^P. A topology of tuples of hyper signals of first genus $H^I_\tau \in R^M$ and of hyper signals of second genus $H^{II}_\tau \in R^M$ are brought in correspondence with the set of measurements concerning the same object and held in the same conditions $Cond$ and in the period $\tau < minT_i$.
- Axiom 3^P. In the space of results of polymetric measuring experiments (in the space of hypercomplex numbers $Z_h \in R^M$) In the space of results of polymetric measuring experiments (in the space of hypercomplex numbers $Cond$ a generalized result of measurement of the object characteristics – charge Z_h as a finite set of values $Z(H, Cond) =< h_1 h_2 ... h_j ... h_M >$ of an assessment of the actual value of object-specific characteristics are designated. This set of assessments is defined on σ–algebra of subsets of tuples $Z =< z_1 z_2 ... z_n >$ as real functions $Z_h = H^I_\tau / H^{II}_\tau \in R^M$.

The comparison of the basics of classical and polymetric measurement theories shows the vital importance of not only PMTA but also their consequences (three of them described in [2] and three new ones presented below). It seems essential to comment on these new practical consequences of PMTA.

2.2. Consequences of polymetric measurements theory axioms

In the general case for an industrial control system or an intelligent system and robot sensing process, it is necessary to have N instruments for each characteristic under monitoring at M possible locations of the components of the object under control. The more practical the application is, the quicker we face the curse of multidimensionality for such system from both technical and financial points of view.

It seems rather evident that in the case when initial polymetric signal – tuple Z has only one element Z_1 we are back to the set of axioms of classical metrology. And this means that polymetric theory is just generalization of classical metrology in the case when the initial measuring signal contains information concerning several physical quantities and their measures.

Furthermore, any polymetric measuring experiment may be presented by the simple model (Z, H, Z_h) – measurable topological space with charge, where the set of tuples Z as space-medium is defined in Axiom 1^P , σ-algebra of subsets H as one of the options of topology H of open subsets of set Z – in Axiom 2^P , and charge Z_h , as real function in space Z on σ-algebra of H [2].

Thus, the result of the polymetric measurement is the set of uniquely defined functions of the sequence of charge Z_h values. On the other hand, polymetric measurement inaccuracy in topological space with charge (Z, H, Z_h) is defined as the diameter of values of the charge $\{Z_h\}$, i.e. least upper bound between pair of elements of set $\{Z_h\}$ [2].

After the introduction of the concept of so-called hyper signals of the third genus $H_\tau^{III} \in R^M$ the novel set of definishings and consequences of the PMTA can be summarised in such a way:

- Definition 8^P . Deviations of a hyper signal of first genus $H_\tau^{I} \in R^M$ is strongly correlated with variations of the value of the physical parameter under control and is inherently the digital assessment of the value of this particular parameter in a fixed time of measurement.
- Definition 9^P . Deviations of a hyper signal of the second genus $H_\tau^{II} \in R^M$ is strongly correlated with variations of the value of the standard of the physical parameter under control and thus is inherently the digital representation of this particular parameter standard in a fixed time of measurement.
- Consequence 4^P Deviations of a hyper signal of the third genus $H_\tau^{III} \in R^M$ are proportional to variations of the value of the feedback control signal of the system in its critical situation under human-machine control and thus may be used as automatic reflexive control system response.

Thus the introduction of the principle of the simultaneous assessment of not only a physical quantity and its standard but also the value of feedback control signal from the same polymetric signal is one of the key conditions for developing appropriate polymetric components application in intelligent automation and smart sensory systems.

The structure of an appropriate perceptive intelligent control and/or monitoring system should be modified correspondingly.

2.3. Advanced structure of PSS

For multi-agent control or monitoring systems and intelligent robots to satisfactorily fulfil the potential missions in diversified applications envisioned for them, it is necessary to incorporate all the above-described advances in the polymetric measurements theory, industrial metrology, AI, Big Data and Machine Learning instruments.

That is why, in contrast to the multi-sensor perceptive agency concept based on the use of several measuring transformers each one of them being the sensing part of each particular agent within the distributed multi-sensor control system (i.e. several perceptive agents in involved perceptive agency), the use of one equivalent polymetric sensor as a part of perceptive hybrid agency was proposed [3]. The concept of Polymetric Perceptive / Control Agency (PPCA) for intelligent system and robot sensing is schematically illustrated in Fig. 1. Such a simplified structure is designated to be used in different industries and technologies. Four layers are shown on the Fig. 1: 1 – Analysis Layer, 2 – Experience and Memory layer, 3 – Executive Layer, 4 – Perceptive Layer.

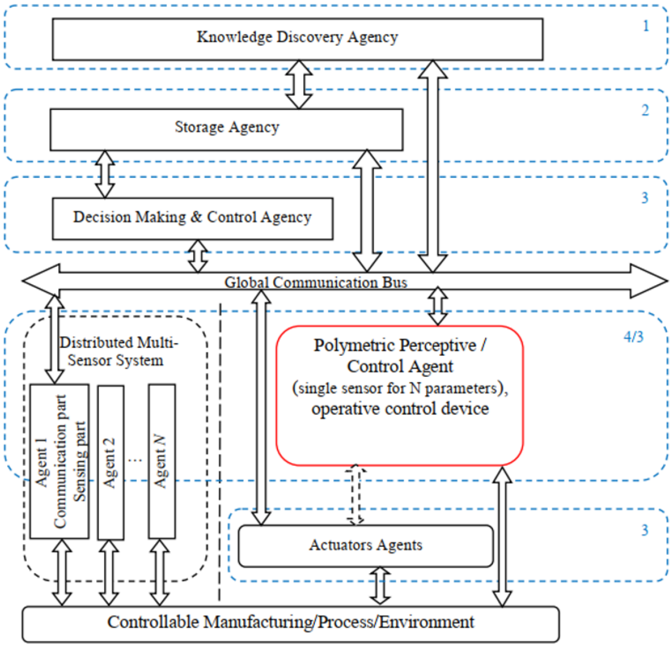

Figure 1: Scheme of the usage of Equivalent Polymetric Perceptive/Control Agent in frames of Hybrid Decision-Making and Control Agency

Each layer includes several agents (or agencies) which are intended for their specialized functions. The explanation of the scheme is reasonable to explain in the opposite order.

Perception agency is realized through the usage of a set of required sensors or/and PSS. As it was mentioned, in contrast to the classical systems, the PSS requires, for example, only one sensor for the measurement of all the necessary parameters of the controllable object. PPCA includes required model to obtain all states parameters of the controllable object and their uncertainties and can act as a controller to manage the actuators operatively autonomously or take no action (if required). All the information about measured and estimated parameters of controllable object are transmitted through available communications channels (communications bus) to Decision Making and Control Agency (DMCA) which is at level 3. DMCA is usually MCU or preprogrammed PLC which realize calculations and/or produces control actions for current control algorithm realization. The information about measured parameters, steps taken, external to the system information is time-scaled and logged using Storage Agency – layer 2. Usually, Storage Agency is realized as a database or distributed database in the cloud. The stored data is a resource available for processing and analysis. Layer 1 includes Knowledge Discovery Agency (KDA) which stands for Analysis of all gathered data and creation of algorithms and rules for DMCA and PPCA. KDA can be used both for online and offline data analysis. It executes several Machine Learning and Preprocessing algorithms to reach goals user defines. Layer 0 is present but not shown. Layer 0 includes the information from users or other agencies: initial setpoints, objectives, criteria and various input data. KDA can execute data preparation (selection, filtering and smoothing, normalization, frequency-domain processing, etc.), feature extraction related activity (model-based analysis, correlation/statistical parameters calculation and modelling, Principal Component Analysis, etc.), feature selection, classification and evaluation of obtained models/results. The results of KDA is an algorithm/knowledgebase / neural network/classification algorithm or a set of models that are transferred to DMCA and PPCA in a standardized form of deployable models. The solution about model applicability and deployment is done on the basis of the evaluation and validation of the model. The essential advantage of the proposed solution is that models can be synthesized and evaluated/optimized for a specific application using collected data about the object and its parameters and behaviour.

Therefore, if we assume that traditional and polymetric sensory systems are equivalent in the measurement information quality and reliability (systems are interchangeable without any loss of measurement information quality), it is evident that polymetric system has the advantage in the measurement channels number. The cost criterion can be used for the comparison of the efficiency of traditional and polymetric sensory systems. And as it can be seen from the described above LASCOS example, the polymetric sensory system efficiency is two times greater than the efficiency of the traditional sensory system ($E_{TSS/PSS}$ = 44/22 = 2). It is worth mentioning that this comparison of the system efficiency is very rough, and it is used only for the demonstration of the main advantage of the polymetric sensory system [2, 3].

It should be noted that according to PSS can be reconfigured to «sense» new parameters (indirectly) or increase sensitivity for the required parameter with the use of «knowledge» from KDA. Even if the polymetric sensor has a very low sensitivity to some critical parameter or it can be used with a high level of uncertainty. It still can be used for monitoring purposes as an additional source of information about the object, in the form of indicator or its equivalent. The described technique also facilitates the concept of «measurement as a service» when not a hardware is being sold but the result of measurements and estimations and uncertainty evaluation. PSS can be realized as a sensing part installed on a controllable object and a «soft» sensor – a model or an algorithm for processing the signal or multiple signals and estimation of required parameters and their uncertainties. Signal or a set of signals is transmitted to the upper level where appropriate models for parameter estimation are used. In response to such a request, the upper-level system outputs a set of estimated parameters, their uncertainties and required control signals, etc. In this case, the informational flows can be directed through secure internet channels and cloud computing technologies [19, 20].

3. Results and Industrial Applications

Evident practical success had been achieved during wide deployment of SADCO™ polymetric systems for monitoring of a variety of multiple both quantitative and qualitative indicators of different liquid or loose ship cargoes. In these systems, single polymetric sensors for measuring more than three of the mentioned indicators were used. Such an approach also showed positive technical and commercial results in remote control of complex technological processes for oil production and refinery control, storage, and commercial stock-taking. Later, the positive experience was gained in application of PSS within another onshore technologies and entities also was a success from efficiency, reliability, serviceability point of view.

3.1. Naval applications

One of the first polymetric sensory systems was designated for onboard ship loading and safety control (LASCOS) for tankers, fishing, offshore, supply and research vessels. The prototypes of these systems were developed, industrialized, and tested during full-scale sea trials in the early 90-es of the last century. These systems have an intricate hybrid polymetric sensing subsystem (from the "topos-chronos" compatibility and accuracy points of view) rather.

That is why these systems are also successfully providing commercial control of cargo handling operations onshore and onboard the ship. The structure of the hardware part of LASCOS for a typical offshore supply vessel is presented in [2, 3]. It consists of the following: operator PC with sensor screen interface; a set of sensors for ship draft monitoring; a set of polymetric sensors for fuel-oil, ballast water and other liquid cargo quantity and quality monitoring and control. Also, it includes radar complex with antenna, display and a keyboard; onboard anemometer; a set of polymetric sensors for liquefied LPG or LNG cargo quantity and quality monitoring and control; switchboards of the subsystem for actuating devices and operating mechanisms control; a basic electronic block of the subsystem for liquid, liquefied or friable cargo monitoring and management and a block with the gyroscopic sensors for real-time monitoring of dynamic parameters of the ship.

The structure of the hardware part of LASCOS for a typical offshore supply vessel is presented in Figure 2.

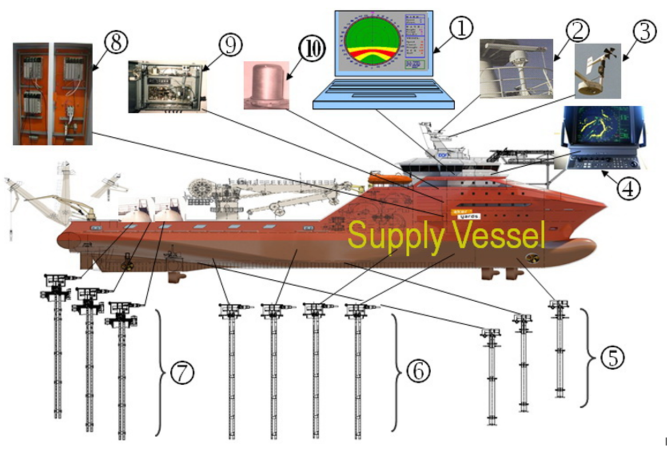

Figure 2: The general structure of LASCOSS hardware elements

It consists of the following components: operator workplace (1); a radar antenna (2); an onboard anemometer (3); the radar display and a keyboard (4); a set of sensors for ship draft monitoring (5); a set of polymetric sensors for fuel-oil, ballast water and other liquid cargo quantity and quality monitoring and control (6); a set of polymetric sensors for liquefied LPG or LNG cargo quantity and quality monitoring and control (7); switchboards of the subsystem for actuating devices and operating mechanisms control (8); a basic electronic block of the subsystem for liquid, liquefied and loose cargo monitoring and control (9); specialized electronic block with the sensors for real-time monitoring of parameters of ship dynamics (10).

The structure of the software part of the typical sensory intelligent LASCOS of the above kind is also described in [3]. It consists of three main elements (see Fig. 3): a sensory monitoring agency (SMA) which includes three other sensory monitoring agencies – SSM (sea state, e.g. wind and wave model parameters), SPM (ship parameters) and NEM (navigation environment parameters); an information environment agency (INE) including fuzzy holonic models of ship state (VSM) and weather conditions (WCM), and also data (DB) and knowledge (KB) bases; and last but not least – an operator interface agency (OPIA) which provides the decision-making person (DMP) with necessary visual and digital information.

The listed above sensory monitoring subsystems are vital in a ship operations control context, as ship safety refers to the inherently distributed and stochastic perturbation of its state parameters and external weather excitations. Holonic agents are welcome in the onboard LASCOS system design because they provide properties such as autonomy, responsiveness, distributiveness, openness, and redundancy. They can be designed to deal with uncertain and/or incomplete information and knowledge, and this is exceptionally topical for any fuzzy control system. On the other hand, the problem of their sensing has never been under systematic consideration yet. That is why one may assume that the challenges mentioned above have to be combined in an integrated model of sensing of all agents involved, which may enable the complex application of cutting-edge and novel methods for efficient solving of practical tasks. Sensory agent-based computations are adaptive to information changes, and disruptions, exhibit intelligence and are inherently distributed. Thus, polymetric sensory holonic systems inherently may help operational control processes in self-recovery reaction to real-time environmental perturbations. And in such a way polymetric sensor could be efficiently used in much more diversified industrial applications.

As mentioned above, all initial real-time information for the sensory systems is provided to DMP by the holonic agent-based sensory monitoring agency (SMA) which includes three other sensory monitoring agencies – SSM, SPM and NEM. But the hardware part of LASCOS is somewhat redundant, and that's why too expensive and barely acceptable in non-critical operational situations from accuracy and reliability point of view, thus limiting the application of LASCOS mainly for rough sea safety monitoring and also loading-uploading operations in the port conditions. In the first scenario, the functions of the system are to predict safe combinations of ship speed and course in rough sea actual weather conditions. On the safe storming diagram, the seafarer may see three colored zones of "speed-course" combinations: the green zone of completely safe ship speed and course combinations; the dangerous red zone with "speed-course" combinations leading to capsized of the ship with up to more than 95% probability; and the yellow zone with "speed-course" combinations with intensive ship motions, preventing standard navigation and other operational activities including bunkering or similar tasks.

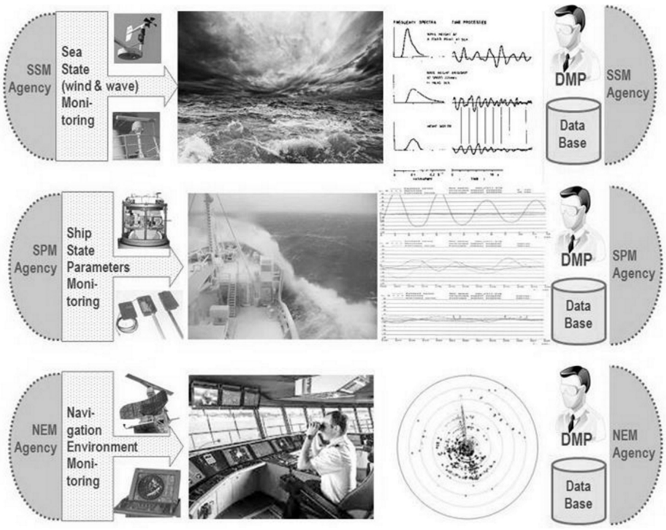

Figure 3: The general structure of LASCOSS software elements and functions

3.2. Maritime end energy infrastructure applications

The first example of the application of PSS for maritime infrastructure technologies is a computer-aided floating dock ballasting process control and monitoring system (SADCO™ Dock) presented in [2]. These systems were designated to ensure effective and safe management of docking operations in the automatic remote mode. The ballast system is one of the most critical systems on the floating dock [10]. The operation must be finely coordinated with the requirements of the marine industry. The mentioned PSS enables to take high-tech solutions to support of safe control and monitoring of the dock ballast system and connected systems. This solution provides the safe and reliable operations of dock facilities in harsh real-life conditions, reduces risks for vessels and generates both operational and financial benefits to customers.

The main interface window of the system contains the technological equipment layout and displays the actual status of valves, pumps, etc. This interface also includes the toolbar, the information panel and the specialized interface containing control elements. So, it is possible to start, change parameters or stop technological processes by clicking a particular control element. The user interface enables the operator to supervise and control every detail of any technology process efficiently. All information concerning the dock and docked ship safety, other operations monitoring and control, event and alarm management, database management or message control are structured in functional windows.

The key advantage of the system is that it can be programmed for various operations scenarios and operation patterns for each dock with its specificity. In ideal conditions, dockmaster can control all the data and only select preprogrammed operations patterns with some tunable data. The data collected during the operations is stored locally and can be used for future training process (not only for dockmasters training but for system training too – VSM for the dock) or operations pattern generation. This feature allows users to save time on typical operations and optimize hardware usage.

Latest versions of the dock-system continuously get additional functionality and updates of the corresponding software. E.g., for correct operation planning, it is necessary to obtain information about the current state of pipelines along with the ballast tanks parameters, valves and pumps parameters. This information gives more flexibility to predict the state of the controllable object and plan the operation cycle more accurately and reliably using internal models: flow and pipeline models included as subsystems into complete dock state model. Additionally, the functionality of dry compartments control was added for leakage control and periodically flooded compartments. This feature gives more information for the dockmaster. It can be used to precise the deformation models, especially in non-standard situations, when the object trajectory must be calculated in the uncertain conditions.

Another example of the successful polymetric sensing of computer-aided control and monitoring systems is connected with different marine/shore terminals (crude oil, light and low-volatility fuel, diesel, liquefied petroleum gas, grain) and even with bilge water cleaning shops [2, 12]. Such polymetric sensing allows simultaneous monitoring of practically all the necessary parameters using one sensor for each tank, silo, or other reservoirs. Especially these systems are useful if the objects are spatially distributed or their structure/parameters can be dynamically transformed, and the user needs the current information about all the operations during transportation and storage. Collected by the PSS data can be processed locally, and the result generated can be presented for the local users. Still, the whole balance and «process owner view» the distributed data collection and processing system may also be used. The critical moment of such PSS usage is that during storage and transportation process, the characteristics of cargo can be changed, and it must be controlled on each stage of the process – see Fig. 4 for description.

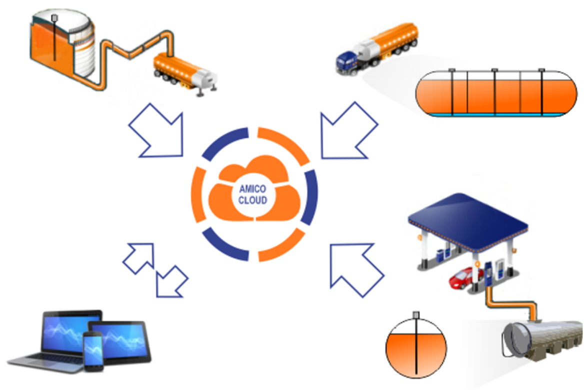

Figure 4: Generalized scheme of data collection and processing of the current information from the liquid's storage and transportation hubs

During transportation from manufacturer to the end-user liquid fuel can be transported by 2-3 types of transport and can change its storage several times, can be diluted, etc. On each stage, the parameters of the controllable fuel or liquid (e.g. palm oil) must be controlled and checked by the process holder to ensure that the cargo is in safe and operation is going according to plan. Cloud-based platform and corresponding applications give the possibility to collect the data from various sources, process collected data and form views and features needed by each class of clients. Another critical aspect of the use of a cloud-based platform is in the possible continuous learning of the system used and related to «big data» instruments. As the data collected can be processed by various methods - various models of processing collected data for multiple properties calculation can be generated. All the developed models can be verified on a control sample. If results of a verification are acceptable – the model and appropriate applications can be deployed into the process, enhancing the PSS usage effect many times.

Namely, a single PSS can be used for control of a set of the following characteristics:

- The level, separation level of the non-mixed media and the online control of upper/lower critical levels and volume of the corresponding cargo in each tank.
- The temperature field in the media, the temperature of the product at fixed points.
- Density, octane/cetane number of fuels, the propane-butane concentration in LPG, corresponding octane number, presence, and percentage of water (including aggressive chemicals – acids, alkalis, etc.).

The main progress in diversification of PSS application was achieved in very topical tasks of operational control of quantitative and qualitative parameters of aviation fuels, Liquefied Petroleum Gas (LPG) terminals operation and safety control systems (SADCO™ GNS) and borated water parameters control in a spent fuel pool at the nuclear power plant under harsh conditions (increased radioactivity, high temperatures and pressure values). The main advantage of the developed polymetric system is that the sought-for fuel quality parameter is functionally related with several operatively evaluated from polymetric sensor hyper signals such as complex dielectric permittivity, amplitudes of pulse components of polymetric signal, time delays between this pulses, etc.). The combined use of operatively evaluated spectral and temporal parameters allows correct calculating of essential fuel quality parameter Q [21].

LPG is an important energy carrier and must be controlled on each stage of the path from the gas-producing plant to the end-users. LPG is a specific product that significantly changes his properties during its storage and transportation, and those properties must be measured [22]. Main controllable parameters during custody transfer are volume and mass of the LPG transferred and related quality parameters – as the density of the phases and chemical composition. The typical approach of operative LPG parameters estimation in pressurized reservoirs is to use level sensors, density sensors for liquid and gas phase and the level sensor for water (if present), pressure sensor, etc. It's also necessary to control the temperature of the liquid and gas phase for temperature volume correction. The proposed method was used to collect the measurement data from various sensors and user inputs (data, related to the parameters that were not directly measured during custody operations – such as chemical composition or the source of the product, data about density of the product). This data was combined with the data from polymetric sensors and corresponding features and models where generated. Via a comparison of calculated and level sensors data, automatic correction functions for level sensors were generated. Proposed models were evaluated on the historical data about errors collected during regular system operation. PSS was improved by applying new knowledge mined from collected historical data. Another example of the results obtained from is an equation that connects the dielectric constant of the vapour phase of the LPG ε_v with its density ρ_v :

$$\varepsilon_v = 1 + 0.00109747 \cdot \rho_v. \quad (1)$$

This data can be used as an alternative path for the LPG vapour phase density estimation. Comparison of the results of the model with the data from other sources showed a relative error of less than 0.7%. It should be noted that if LPG is not clear, includes water and it is vaporized/condensated in the reservoir – the equation (1) cannot be applied because of the low accuracy reasons.

As a result, a considerable increase of the measuring performance factor $E_{TSS/PSS}$ was achieved in each application of PSS up to 4-6 times [2]) with the essential concurrent reduction of the number of instruments and measuring channels of the monitoring system. All the customers (more than 50 objects in Ukraine, Qatar, Russia, Uzbekistan, etc.) reported safety increase and commercial benefits after intensive SADCO™ polymetric monitoring systems deployment.

Unique PSS systems «UNITEK-NPP» for Nuclear Power Plants (NPP) safety control via measuring the cooling water level in spent nuclear fuel storage basins are designated to operate in normal conditions, disturbance and accident conditions, including «heavy» accidents, are successfully working on all 15 NPP units of Ukraine. The essential advantage of such a system is in its high reliability and self-diagnostics features. The PSS design is based on best practices of the guided wave radar technology - as preferred technology from the market leaders for spent fuel pool level measurement [23]. Fig.5 shows the structure of PSS for usage in harsh conditions.

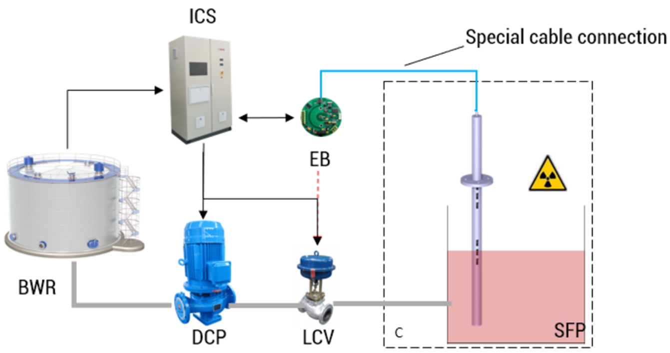

Figure 5: The structure of the PSS channel used in nuclear power plants

Electronics block (EB) of PSS is in a «safe» zone – outside the containment (marked as C in Fig. 5). The sensing part of the system is placed in the spent fuel pool (SFP) – where harsh conditions and various accidents can occur. EB produces signals for Information Control System (ICS) and can be used as a source of a control signal for level controlled valve (LCV) and Distance Controlled Pumps (DCP) for pumping of the borated water from Borated Water Reservoirs (BWR) into SFP. Unlike standard time-domain reflectometry methods (e.g. [24]), the advanced technology and technique, based on multiple reflections are used. This technique allows to reduce the error occurred when the harsh conditions are present and to detect a change in the state of some sensor parts – as a self-diagnostics method.

3.3. Prospective industrial PSS applications

Some special PSS were developed, tested, and integrated into control and monitoring systems before 2000-2010 in limited numbers for the following industrial applications:

- real-time remote monitoring of the production process of motor lubrication oil (quantitative and qualitative control of the components depending on time and real temperature deviation during the production process).
- real-time remote control of aggressive chemicals at a water purification shop of the nuclear power stations (quantitative and qualitative control of the components depending on time and real temperature deviation during the production process), etc.

Further diversification of PSS application in different new fields and further improvement of already industrialized systems could be achieved via intensive development of the axiomatic theory of polymetric measurements and digitalization of all PSS structural components.

Other prospects are connected to utilization of neoteric high precision and reliable radars which allow finding out unique hyper signals of the third genus directly correlated to optimal steering command for ship autopilot in parallel assessing of spectral parameters of wave and wind perturbations. Then the structure of both hardware and software parts of the above described onboard LASCOS system must be drastically changed, making it much simpler and more effective from practically all points of view. It will be reasonable to consider some latest developments in techniques, algorithms and hardware that can be applied to extend PSS informativeness and efficiency including a possible adaption of technologies for the development of non-trivial polymetric sensors, e.g. [25, 26, 27].

4. Conclusions

This paper has been intended as a general presentation of new achievements in the development of the axiomatic theory of polymetric measurements and their influence on potential diversification of application of newly developed and already industrialized polymetric components (subsystems) in intelligent robotics and embedded control systems.

Rapidly developing and very topical area of building up various intelligent robotics and embedded control systems needs more and more innovations in the theory, software and hardware development and optimization. For solving such a topical objective, one needs to implement the leading-edge solutions for each component of such systems, including their embedded sensory subsystems.

Despite intensive investments and investigations carried out in the described field last decade, many aspects of the theory and practice of PSS application in different technologies from a metrological point of view and certification regulations requirements remain to be better defined.

After the enthusiasm that characterized the first decade of the discovery that more than two parameters of media may be measured by one single instrument (polymetric sensor), it is now time to start a serious and coordinated action to define how to diversify such sensors application for more and more industrial problems, especially for embedding PSS for intelligent robotics and smart automation. Actual progress in such issue can be achieved only in frames of shared international research programs involving investigators from all over the world and making the results widely available.

References

[1] Y. Zhukov, Solitonic models of polymetric monitoring systems, Proc. of International Conf. "Shipbuilding problems: state, ideas, solutions" (1997) 251–252.

[2] Y. Zhukov, Polymetric Systems: Theory and Practice, Atoll, 2012.

[3] Y. P. Kondratenko, R. J. Duro, Advances in intelligent robotics and collaborative automation, in: Advances in Intelligent Robotics and Collaborative Automation, River Publisher, 2015, pp. 1–364. URL: https://doi.org/10.13052/rp-9788793237049. doi:10.13052/rp-9788793237049.

[4] A. Schütze, N. Helwig, T. Schneider, Sensors 4.0 – smart sensors and measurement technology enable industry 4.0, Journal of Sensors and Sensor Systems 7 (2018) 359–371. URL: https://doi.org/10.5194/jsss-7-359-2018. doi:10.5194/jsss-7-359-2018.

[5] D. G. Pascual, P. Daponte, U. Kumar, Handbook of Industry 4.0 and SMART Systems, CRC Press, 2019.

[6] R. Frank, Understanding smart sensors, Artech House, 2013.

[7] R. Taymanov, K. Sapozhnikova, What makes sensor devices and microsystems “intelligent” or “smart”?, in: Smart Sensors and MEMs, Elsevier, 2018, pp. 1–22. URL: https://doi.org/10.1016/b978-0-08-102055-5.00001-2. doi:10.1016/b978-0-08-102055-5.00001-2.

[8] Y. P. Kondratenko, V. V. Korobko, O. V. Korobko, Multisensor data acquisition system for thermoacoustic processes analysis, in: Proceedings of the 6th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems, IEEE, 2011. URL: https://doi.org/10.1109/idaacs.2011.6072710. doi:10.1109/idaacs.2011.6072710.

[9] Y. Kondratenko, O. Korobko, O. Kozlov, O. Gerasin, A. Topalov, PLC based system for remote liquids level control with radar sensor, in: 2015 IEEE 8th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), IEEE, 2015. URL: https://doi.org/10.1109/idaacs.2015.7340699. doi:10.1109/idaacs.2015.7340699.

[10] A. Topalov, O. Kozlov, Y. Kondratenko, Control processes of floating docks based on SCADA systems with wireless data transmission, in: 2016 XII International Conference on Perspective Technologies and Methods in MEMS Design (MEMSTECH), IEEE, 2016. URL: https://doi.org/10.1109/memstech.2016.7507520. doi:10.1109/memstech.2016.7507520.

[11] N. V. Kirianaki, S. Y. Yurish, N. O. Shpak, V. P. Deynega, Data Acquisition and Signal Processing for Smart Sensors, John Wiley & Sons, Ltd, 2002. URL: https://doi.org/10.1002/0470846100. doi:10.1002/0470846100.

[12] S. Cavalieri, L. Fasanotti, S. Ierace, C. E. Pereira, M. Zuccolotto, A biomimetic approach to distributed maintenance management based on a multi-agent system, in: Industrial Agents, Elsevier, 2015, pp. 361–379. URL: https://doi.org/10.1016/b978-0-12-800341-1.00020-6. doi:10.1016/b978-0-12-800341-1.00020-6.

[13] P. Leitão, Agent-based distributed manufacturing control: A state-of-the-art survey,

Engineering Applications of Artificial Intelligence 22 (2009) 979–991. URL: https://doi.org/10.1016/j.engappai.2008.09.005. doi:10.1016/j.engappai.2008.09.005.
[14] K. Hossain, M. Milton, B. Nimmo, Metrology for the 2020s, 2013.
[15] S. Russell, P. Norvig, Artificial intelligence: a modern approach (2002).
[16] L. Monostori, J. Váncza, S. Kumara, Agent-based systems for manufacturing, CIRP Annals 55 (2006) 697–720. URL: https://doi.org/10.1016/j.cirp.2006.10.004. doi:10.1016/j.cirp.2006.10.004.
[17] F. Amigoni, A. Brandolini, G. D'Antona, R. Ottoboni, M. Somalvico, Artificial intelligence in science of measurements: From measurement instruments to perceptive agencies, IEEE Transactions on Instrumentation and Measurement 52 (2003) 716–723. URL: https://doi.org/10.1109/tim.2003.814694. doi:10.1109/tim.2003.814694.
[18] E. Alpaydin, Introduction to machine learning, MIT press, 2020.
[19] M. N. Birje, P. S. Challagidad, R. Goudar, M. T. Tapale, Cloud computing review: concepts, technology, challenges and security, International Journal of Cloud Computing 6 (2017) 32. URL: https://doi.org/10.1504/ijcc.2017.083905. doi:10.1504/ijcc.2017.083905.
[20] G. Kumar, A review on data protection of cloud computing security, benefits, risks and suggestions, United International Journal for Research and Technology (2019) 26–34.
[21] Y. Zhukov, B. Gordeev, A. Zivenko, Polymetric method of operational control of qualitative and quantitative characteristics of aviation fuels, in: Proc. of 5th World Congress: Aviation in the XXI century, , 2012.
[22] O. Zivenko, LPG ACCOUNTING SPECIFICITY DURING ITS STORAGE AND TRANSPORTATION, Measuring Equipment and Metrology 80 (2019) 21–27. URL: https://doi.org/10.23939/istcmtm2019.03.021. doi:10.23939/istcmtm2019.03.021.
[23] S. Ansari, Building Computer Vision Applications Using Artificial Neural Networks, Apress, 2020. URL: https://doi.org/10.1007/978-1-4842-5887-3. doi:10.1007/978-1-4842-5887-3.
[24] V. Melnikov, V. Ivanov, I. Teplyashin, M. Timonin, Development and study of a microwave reflex-radar level gauge of the nuclear reactor coolant, Nuclear Energy and Technology 4 (2018) 185–190. URL: https://doi.org/10.3897/nucet.4.31857. doi:10.3897/nucet.4.31857.
[25] B. Zhang, Y. Pi, J. Li, Terahertz imaging radar with inverse aperture synthesis techniques: System structure, signal processing, and experiment results, IEEE Sensors Journal 15 (2015) 290–299. URL: https://doi.org/10.1109/jsen.2014.2342495. doi:10.1109/jsen.2014.2342495.
[26] J. A. Cantoral-Ceballos, N. Nurgiyatna, P. Wright, J. Vaughan, C. Brown-Wilson, P. J. Scully, K. B. Ozanyan, Intelligent carpet system, based on photonic guided-path tomography, for gait and balance monitoring in home environments, IEEE Sensors Journal 15 (2015) 279–289. URL: https://doi.org/10.1109/jsen.2014.2341455. doi:10.1109/jsen.2014.2341455.
[27] S. Wang, J. Song, J. Lien, I. Poupyrev, O. Hilliges, Interacting with soli, in: Proceedings of the 29th Annual Symposium on User Interface Software and Technology, ACM, 2016. URL: https://doi.org/10.1145/2984511.2984565. doi:10.1145/2984511.2984565.