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Faculty of Mechanical Engineering

10th International Scientific Conference

IRMES 2022

Research and Development of Mechanical Elements and Systems

PROCEEDINGS

"Machine design in the context of Industry 4.0 – Intelligent products"

Association for Design, Elements and Constructions

26 May 2022, Faculty of Mechanical Engineering, Belgrade, Serbia

10th International Scientific Conference - IRMES 2022

Research and Development of Mechanical Elements and Systems

PROCEEDINGS

Machine design in the context of Industry I4.0 – Intelligent products

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Dear Ladies and Gentlemen, Colleagues, Participants and Friends of IRMES 2022

The International Conference on Research and Development of Mechanical Elements and Systems – IRMES is organized under the auspices of the Association for Design, Elements and Constructions (ADEKO). The Conference has a long tradition of gathering scientists, researchers, academics, engineers and industry representatives, intending to exchange and share knowledge, ideas, experiences, innovations and research results in the field of engineering design, machine elements and systems.

So far, there have been nine editions, organized by several universities – members of the ADEKO association:

1995 – University of Niš, Faculty of Mechanical Engineering
1998 – University of Belgrade, Faculty of Mechanical Engineering
2000 – University of Podgorica, Faculty of Mechanical Engineering
2022 – University of East Sarajevo, Faculty of Mechanical Engineering
2004 – University of Kragujevac, Faculty of Mechanical Engineering
2006 – University of Banja Luka, Faculty of Mechanical Engineering
2011 – University of Niš, Faculty of Mechanical Engineering
2017 – University of Montenegro, Faculty of Mechanical Engineering
2019 – University of Kragujevac, Faculty of Engineering

More than a thousand authors participated in previous IRMES conferences, with more than a thousand papers published in total. The current IRMES conference was supposed to be held in 2021. However, due to the COVID-19 epidemic, it was postponed to 2022.

The main topic of the IRMES 2022 conference is „Machine design in the context of Industry 4.0 – Intelligent products“. For sociologists and philosophers of science, the question remains whether the concept today, most commonly called Industry 4.0, is the true fourth technological revolution or the development/continuation of the third technological revolution – through further application of computers in production and logistics. It is indisputable that the essential question of this concept is the following: how do we introduce intelligent production in the industry? This consequently opens up new questions in the field of engineering design, theory and practice of technical systems and machine elements, and innovative product development – in the environment of the now global comprehensive Industry 4.0 concept or the Japanese answer to this concept – Society 5.0.

Teaching subjects and modules, such as Mechanical Elements, Machine Design, Innovative Product Development and others, has been the basis and generator of previous technological revolutions. Therefore, the question arises as to how to develop and improve the existing content of these subjects, but, also, what the best way for knowledge transfer is to keep the listed subjects as a driving force behind further development and improvement of philosophy and concept of Industry 4.0 (ie. how to implement new teaching methods, lessons, exercises, student projects, laboratory work, evaluation).

Taking into account the previously described facts, it is clear why an exchange of opinions, experiences and results between experts in the Industry 4.0 area is essential for social and industrial development. One of the best ways to do that is via public debate at international conferences, such as IRMES 2022, which we are very glad and proud to host and organize this year.

Belgrade, 26 May 2022

Prof. Dr. Radivoje Mitrović

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CONTENTS

PLENARY LECTURES

INVITED LECTURES

INDUSTRY 4.0

MACHINE ELEMENTS AND SYSTEMS

ENGINEERING DESIGN, NEW TECHNOLOGIES

10th International Scientific Conference
IRMES 2022
"Machine design in the context of Industry 4.0 – Intelligent products"
26 May 2022, Belgrade, Serbia

MICRO AND NANO TECHNOLOGIES (MNTs) IN INDUSTRY 4.0 COMMUNICATION SYSTEMS

Nemanja PAJIĆ
Nikola KOTORČEVIĆ
Nenad GRUJOVIĆ
Fatima ŽIVIĆ

Abstract: *This paper presents some solutions used in communication systems of Industry 4.0 context that are based on micro- and nano-technologies. There is a significant need for miniaturized multifunctional components that can be incorporated within different system elements in an existing industrial production system, without altering the basic system function. A range of micro- and nano-devices have been studied to serve as the foundation for development and deployment of sensor network that simultaneously can provide some other functions, like sensing, actuation and/or energy harvesting. However, no high amount of such devices has been incorporated in real industrial systems so far. Big data in Industry 4.0 strongly relies on a possibility for real-time data collection, which is based on sensor network. Physical positioning of such network throughout the production facilities can be a very challenging task for companies. Advanced multifunctioning sensors are usually based on utilization of advanced materials very often incorporating micro- and/or nano-materials. Fiber-optic sensors are widely used and commercialized components used in quality control in civil engineering structures, quantitative chemical processes, health and safety monitoring of composite materials or structural health monitoring. Advantages of miniaturized fiber-optics sensors are: smaller size, lower power consumption, higher sensitivity and faster response.*

Keywords: *microsensors; nano-enabled sensors; fiber-optic sensors; energy harvesting; quality control*

1. INTRODUCTION

Industry 4.0 can be considered as digitalization of production, managerial, and administrative processes and it is based on 4 principles: interconnectivity, information transparency, technical support, decentralized decision making [1]. Interconnectivity is based on connecting production equipment, measurement equipment, sensor/monitoring systems, support systems with computing systems and smart devices [1]. This way all collected information can be software processed and available to the system users in a form of simple, precise and real-time information[1].

For some quality processes sensing equipment can be expensive, but even bigger challenge can be sensor integration. For some processes conventional sensors cannot be integrated due to its size (for small systems like proton-exchange membrane (PEM) they are too big), or because they cannot withstand the environment (temperature, acidity, moisture, pressure, etc.). Micro and nano technologies (MNTs) provide wide range of sensors on micro and nano level which can be less pricy and more precise than conventional sensors. Micro and nano sensors have advanced in the recent years and are capable of sensing/monitoring many different characteristics, harvesting energy, and interacting with micro and nano environment. This paper presents micro and nano-based sensors which can be applied to sense:

- Different gasses,
- pH value,
- Moisture content,
- Humidity,
- Shape changes,
- Strain,
- Acoustics,
- Temperature,
- Pressure,
- Vibration characteristics,
- Voltage,
- Current,
- Flow distribution,
- Ions.

Large number of micro and nano sensors can be produced relatively inexpensively. This means that a number of these small sensors can be deployed to provide measurement data for a single process. Human brain can process and understand only limited amount of data [2]. To understand large amount of measurement data 'Big data' analytics can be applied. Big data analytics is a method of collecting, sorting, understanding and processing large amount of data [2]. Chaotic systems are often unpredictable and sensitive to initial conditions, so when there is a lot of data, unlike human brain, Big data analytic system can process them and predict the outcome [2]. Big data analytics can be successfully paired with MNT sensing systems for the purpose of industrial monitoring of parameters and predicting of the outcome in the production, maintenance, health and safety, and quality control processes.

Optic systems are superior in comparison to metal components regarding the data transfer and infrastructure longevity [3]. Optic systems are not prone to oxidation, they have low attenuation, and electromagnetic forces do not interfere with data transfer [3].

2. IMPLEMENTATION CHALLENGES OF INDUSTRIAL INTERNET OF THINGS (IIoT)

MNT sensors can be very successfully applied as a part of industrial monitoring systems. Industrial equipment generates a lot of data, second by second, measurement by measurement. Industry 4.0 steers the industry leaders to strive for the great level of data availability and accessibility [2]. Industrial Internet of Things is a term which describes interconnection of industrial equipment and cyber systems [4]. In order to provide all of the needed information in a real time manner, regardless of the location of the person which requires data, IIoT must be utilized [5]. Sometimes the amount of measurement data is so large that it would be impossible for an expert to understand the meaning behind the data set. Number of methods have been studied in relation to Big data analytics and its structures that would enable comprehensible and usable information [5]–[7]. In case of industrial production process, like welding operation, one could use MNT sensors to track changes in temperature, voltage, arc current, pressure, welding head speed and position, welded object shape changes and many more. Every tenth of a second (or faster) a measurement can be updated, meaning that Big Data can be used to structure the data and IIoT approach can provide data storage, accessibility and availability. However, for a prediction of welding defects, only comprehensive description of the process parameters, within the specification limits, can be currently used. If the process parameters are within the specification limits and some defects still occur, artificial intelligence can be applied to find the link between the process parameters and the outcome [1]. In order to apply this kind of solution, data is required. Available data can be characterized based on the following criteria [8]:

- Amount of available data,
- Dynamics of data creation and upload,
- Diversity of the data,
- Data accuracy,
- Form of the data.

In case of insufficient amount of data, AI predictive system cannot be calibrated for all of the possible variations and defects. This will lower the accuracy of the AI algorithm [9]. If measurement data is created very fast, one after another, but uploading to the system takes a lot of time, or the system waits until it reaches 100 measurements to upload the data, AI might not have enough time to make a decision before releasing the part to the next station. If data input is done from multiple sources or data is in different forms, such as: different file extensions; one measurement is in millimeters and the other in microns; a part of measurement data is written in paper only; some of the data is only manually downloadable from the machine or via USB drive transferred to the system, many difficulties can occur, or additional steps in data preparation might be required. Sometimes the laboratory tests results are only written in paper, stored in the self-files, this making the AI integration more difficult. Sometimes, it is impossible to match the process parameter data with test result data. There must be a link between the two, like a serial number or similar, which might not be collected during the laboratory test, or the equipment is not saving historical data, and process parameters have only a time label but are not linked to the serial number.

Significant challenge of the 4th industrial revolution is lack of skilled experts for integration of AI solutions. Another challenge in the application of AI solutions is a choice of the appropriate algorithm [10]. To have a functional system, AI method must be matched with the used data, and the desired task. There are many methods which can be applied in predictive AI systems, such as [9]:

- Taguchi method,
- Response surface method (RSM),
- Artificial neural network (ANN),
- Genetic algorithm (GA),
- Fuzzy logic systems,
- Adaptive neuro-fuzzy inference systems (ANFIS),
- Particle swarm optimization (PSO).

For the small and medium enterprises (SMEs) it is not economically viable to employ Data Analyst or an AI expert. Researchers have analyzed a solution which can be used by non-experts. The idea is to choose one of the of-the-shelf solutions and make the process faster and easier [10].

Another challenge in the Industry 4.0 transformation for the SMEs, especially if the company is old and already equipped with the machinery, besides the IT knowledge, willingness and readiness for the Industry 4.0, is the advanced technology, which can be very expensive. Some recent studies proved that integration of inexpensive sensors in the older machine systems can provide very positive results [11], [12]. For the improvement of safety and maintenance performance within SMEs, together with their transformation to smart factory, researchers applied sensor network, IIoT, combined it with a deep learning algorithm and digital twin approach [11]. Even though the investment resources, and the implementation time were very limited, it was proved that it is possible to retrofit an old plant and make it a smart one [11].

3. OPTIC SYSTEMS

In order to meet the requirements of time sensitive applications (for Industry 4.0 and 5G fronthauling), networks must be trustable, highly reactive and jitter free [13]. The goal of fifth generation (5G) networks is to cover wide range of networking cases: from ultra-low latency applications used in sensor networks (or the Internet of Things in general) to standard mobile access [13]. To decrease the latency due to physical propagation of the signals, new end-to-end architecture is required [13].

Since the light is one of the main carriers of information in communication, aim of many studies is to improve its efficiency. Orbital angular momentum (OAM) has recently become researched as degree of freedom for multiplexing data in free space, at nanoscale and optical fibers [14]. Downside of optical free-space communication using OAM multiplexing is that it suffers from scattering caused by microparticles in the atmosphere [14]. Gong et al. demonstrated transmission of color and grey images where scattering conditions were at error rate of <0.08%, which may be step forward in high-performance optical communication [14].

Modern large-scale networks rely on fiber optic networks, mainly due their big transmission capacity [3]. Present-day local computer networks use optical fiber and radio-link as dominant medium, while networks based on copper cabling are decreasing [3]. This is due to a lower security, since copper cables can radiate energy in an unpredictable manner [3]. Radio-links provide signals radiated by means of antennas which results in better secured information [3]. However, interference still presents problems. With fiber-optic transmission such problems are solved since there is no unwanted emission which would be easy to capture [3]. On the other hand, one of the issues is connection between fiber-optic cables and fiber optics systems and devices [3].

Microwave (MW) components and Reconfigurable and tunable radio frequency (RF) are also studied. For multifunctional tasks in wireless communication systems, reconfigurable microstrip filter–antenna combinations were developed. In order to reduce cost of wireless system and number of components, those devices can be used [15]. It achieves changes in the performance with electronic tuning techniques and such structures are in high demand with development of 4G and 5G applications [15]. Tu et al. demonstrated that antennas with integrated reconfigurable filters can provide radiation properties of antenna while suppressing interference [15].

Miniaturization of optical systems (for imaging and sensing) have become very popular trend, especially in biomedical application, like endoscopic and wearable medical devices [16]. New development of bio-optical systems is achieved through a metasurface-based flat lens (metalens) [16]. MBBs (meta building blocks) have function of subwavelength-spaced scatterers [16]. When MBBs' size, position and shape are tuned, lot of lights basic properties (like: polarization, focal points, phase) can be controlled in high-resolution imaging and sensing [16]. For example, conventional refractive lenses (e.g. in telescopes and microscopes) are usually designed in different shapes, more expensive and bulkier, and require sophisticated fabrication processes (molding, polishing, diamond turning) [16]. On the other hand, phase profile of meta-lens can by modified with MBBs, and with advanced micro-machining processes can be mass produced [16].

Fiber-optic sensors are widely used and commercialized components in areas like: large civil engineering structures, quantitative chemical processes, health and safety monitoring of composite materials and structural health monitoring [17]. Micro-structured optical fiber sensors represent micro-machined and micro-manipulated fiber sensors or microfibers such as tapered fiber structures [17]. Advantages of miniaturized fiber-optics sensors are: smaller size, lower power consumption, higher sensitivity and faster response [17]. There are many different fabrication methods, but one of the frequently used is heating and stretching technique for creation of long fiber taper [17]. Section of standard single mode fiber (SMF) is stretched two linear translation stages while small sector of the fiber is heated by hydrogen gas flame [17]. Whole process is precisely controlled by the computer on the submicron level [17].

Fiber-optic sensors are also often implemented into smart materials as a sensing technology. They can be embedded during the liquid phase of the composite smart material manufacturing process. In polymeric materials or concrete, temperatures rarely exceed 100°C, but in metallic materials, it can reach values above 1000°C- which creates risk of damaging sensor [18]. To avoid such thing, number of methods rely on deployment of metallic coatings which can protect optical fiber during embedding process [18]. Grandal et al. proved that advanced manufacturing brazing process can be used for embedding fiber optic sensor into Tin alloy (SnSb8Cu4) coated ST52 steel metals. Metallic coating for optical fiber protection, used in this technique, could be Ni or Cu. Coating can be 300 μm thin for 2000W laser brazing power and 300 μm for 1500W-1800W (although coatings up to 237 μm were embedded with minimal transmission loss on the fiber) [18]. Other techniques can be based on ultrasonic welding, selective laser melting, manual TIG method etc. [18].

Gallium arsenide (GaAs) is material widely used in the fields of optoelectronics and microelectronics for devices in fiber-optic communication, cable television, vehicle navigation, smart devices in telecommunication and semiconductor light-emitting diodes [19]. It is semiconductor material with advantages, in comparison to silicon, like higher electron mobility, higher temperature resistance, wider bandgap [19]. On the other hand, it has lower values of fracture toughness and elastic modulus which makes it much harder to machine [19]. One of the solutions is implementation of Atomic Force Microscope (AFM) tip-based nanomachining [19]. It is low-cost solution to perform flexible direct writing on a nano-level in single pass in different conditions, like ultra-vacuum, liquid and low temperature or high temperature [19]. This method is applied in creation of nanodots, nano lines, two-dimensional and three-dimensional nanostructures like, for example, hemisphere cavity for light –emitting diodes quantum devices on the GaAs substrate [19].

Sapphire (α-Al2O3) is monocrystalline material with excellent optical, chemical, physical and thermal properties [20]. This makes it good material for LED substrates, laser amplifiers, optical fiber sensors, windows fields. On the other hand, its limited fracture toughness, high hardness and high brittleness are rising prize of production of low-damage sapphire surface [20]. Micro cutting with assistance of ultrasonic elliptical vibrations is technique proven to be effective in processing such material [20]. Degree of cutting groove damage as well as subsurface cracks have lower values for ultrasonic assisted micro cutting, in comparison with conventional cutting [20]. Wang et al. demonstrated in their experiment that width of defects in vibrational micro cutting is 53 μm and in traditional cutting 81 μm [20]. At the same time, average cutting speed is higher and cutting force lower for ultrasonic assisted process [20].

4. POSSIBILITIES OF MICRO AND NANO TECHNOLOGY IN INDUSTRY 4.0

Industry 4.0 concept of the distributed condition monitoring in manufacturing plants is based on the sensor network located throughout the factory and incorporated within the IIoT communication architecture (usually supported by wireless and cloud technologies), as shown in Fig. 1. Advanced communication network is usually based on optic fiber technology. Optic fibers are multifunctional components, with wide application potentials. Their most common industrial applications are data transfer and sensing/ monitoring [17]. Fiber-optic sensors are small, reliable, long lasting (low oxidation), low attenuation, optical signal is not influenced by electromagnetic waves, and they can transmit signals over a great distance [17]. These features open wide variety of possibilities for industrial application. They can be integrated into many processes for continuous monitoring and quality control. Some of the sensing applications provided by Xu et al., 2017 are: detection of hazardous materials, volatile gases, pH value, ions, humidity, and many more Xu et al., 2017. Combination of the precise, continuous measurement in industrial process with Big Data analytics and AI algorithms can constitute very reliable quality control system and predictive system.

For the sensing applications, where the shape change detection of some object is required, such as aircraft wings, robotic joints, critical springs, fiber-optic sensors could provide a great solution. Solution based on helical twisted structure shows very promising results [21]. Its structure allows it to detect directional torsion and vector bending, with the possibility to eliminate influence of strain and temperature comparing wavelength change in the side and the central core [21]. This can be applied on both micro and macro level, and it presents great application potential for the equipment health monitoring and maintenance risks. It is possible to incorporate this solution also in the quality control for many different processes.

One of possible solutions in the Carbon Capture and Utilisation Systems (CCUS) is storage of collected CO_2 in the dried oil wells. Many potential risks were analysed due to potential of seismic changes. In order to avoid potential risks, researchers analysed application of fiber-optic sensor that, over its entire length, could detect changes like: strain, acoustics, temperature, pressure and many more [22]. Monitoring of these parameters could be applied to many industrial processes, such as gas and liquid storages, filling, pressing/stamping, compressed air production, and many more.

Successful experiment was done with the helicopter rotor blade, and monitoring of the blade dynamics. Optical fiber Bragg grating, and direct fiber optic shape sensing monitoring systems proved to be capable of detecting the blade shape change, frequency and vibration characteristics [23]. Same method could be applied for quality control tests during production of rotors, turbines, wipers, wings, spoilers, etc.

Sensing changes in humidity and temperature can be crucial for solid wood furniture industry i.e., solid wood components can vary in length a couple of centimeters per 1 meter when ambient humidity change. Food processing and storing is also very sensitive to temperature and humidity changes [24]. It was proved that changeable length and diameter (CLD) solution are very capable of sensing temperature and humidity changes [24]. If lumber is cut in one building, planks shaped in the second, sanded in the third, and assembled in the fourth facility, significant dimensional discrepancies may occur if the humidity/temperature changes. Network of sensors can be linked to IoT with a protocol that starts water spraying if humidity is low, or heating if it is high.

Rayleigh scattering based optical-fiber sensors are successfully used in lithium-ion battery internal temperature measurement since they can operate even when submerged in electrolyte [25]. Their small size and robust design makes them suitable candidates for the task [25]. Batteries are one of the components with the highest risk in the electric vehicles (EVs). With EVs on the path to become the primary mean of transportation, battery management systems have become very important research topic.

Micro electro mechanical system (MEMS) was utilized in order to produce integrated sensor for lithium ion batteries [26] that can monitor voltage, current, and temperature, with short response time.

Industrial waste water management and mitigation is one of the most important topics for the Health and Safety representatives. Detection of toxic or hazardous substances in the released waste water is very important, such as presence of the arsenic in the water [27]. Many possibilities have been enlightened with the advances in the field of micro motors, and more recently nano motors [28]. Their application possibilities are not investigated nearly enough. They are most usually propelled by some electrical or chemical energy source. Recent researches show that there is a great potential to use renewables to power micro and nano motors, such as wind, solar, light and sound as an external energy source [28].

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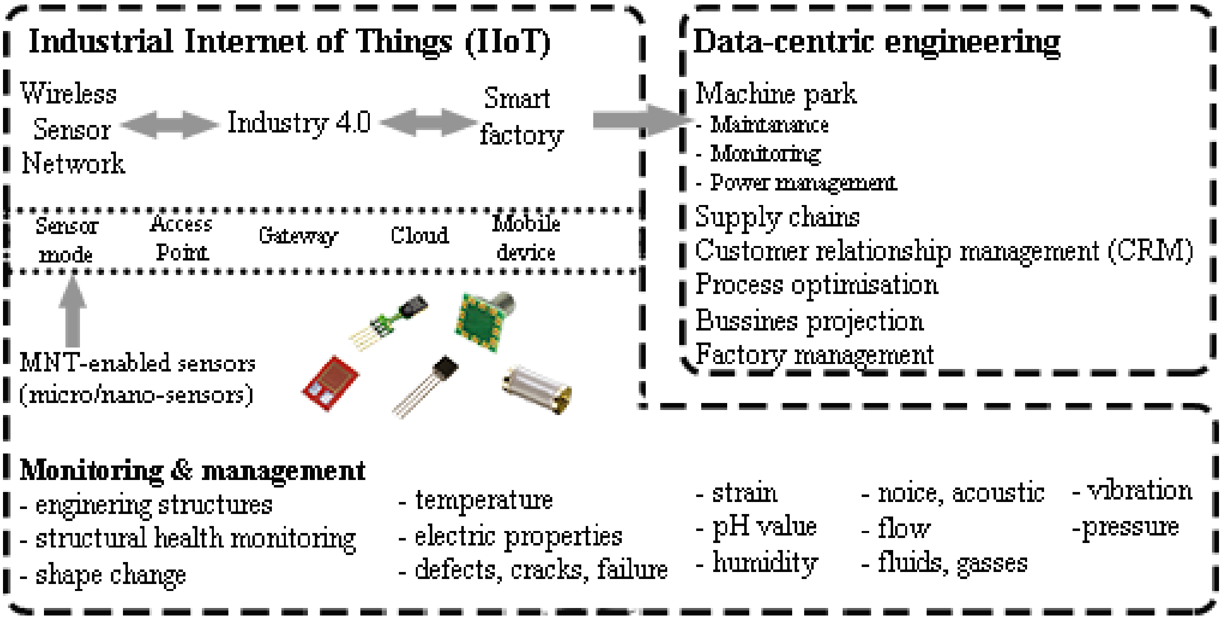

Figure 1 Schematic view of the sensor network role in distributed condition monitoring within the IIoT communication architecture supported by the wireless and cloud technologies

Industrial waste water management and mitigation is one of the most important topics for the Health and Safety representatives. Detection of toxic or hazardous substances in the released waste water is very important, such as presence of the arsenic in the water [27]. Many possibilities have been enlightened with the advances in the field of micro motors, and more recently nano motors [28]. Their application possibilities are not investigated nearly enough. They are most usually propelled by some electrical or chemical energy source. Recent researches show that there is a great potential to use renewables to power micro and nano motors, such as wind, solar, light and sound as an external energy source [28].
Zinc oxide (ZnO) semiconductors can be used in a wide range of sensing applications, including environmental monitoring, biomedical testing (glucose, urea, DNA, PSA, etc.), optical sensing [29], as previously mentioned.
Fuel cell electric vehicles are increasing in popularity day by day. Fuel cells are relatively efficient devices, but the production of hydrogen has many losses with the current state of technology [30]. Water electrolysis can be done in many ways, one being proton exchange membrane (PEM) electrolysis [30]. Advantages of this system are low operating temperature, absence of non-wanted by-products, capability to produce limited amounts of hydrogen, saving on the production costs [30]. This method works in the opposite way compared to fuel cell energy production. Reaction environment is critical for the efficiency and effectiveness of the process [30]. In order to monitor and control the reaction thin film flexible integrated microsensor can be installed in PEM, providing real time measurements of: temperature, current, voltage and flow distribution [30]. Similar sensing technique can be applied to fuel cells, in the process of electricity production.
Oil changes are most common maintenance activities. If oil is not changed regularly many unwanted effects could be caused. When the oil moisture content is increased its permittivity changes, oil ageing can be accelerated, acidity increased and many undesired conditions can occur. These unwanted effects can be avoided by using an interdigitated impedance microsensor [31]. Micro sensor presented in this research could detect moisture content changes in the engine oil and alert the maintenance department to change the oil [31]. This can cut costs on the unwanted maintenance, breakdown line stoppage, delivery delays, or even costs of the oil. If the oil is used while it is good, and not changed preventively this can for sure make some savings.
For pneumatic devices, pressure control is one of the most important characteristics. For plastic bottles blowing, vacuum presses, sheet metal stamping, leak tests, dosing/filling operations pressure control is crucial factor. Novel design based on dual-gate graphene field-effect transistor with a vertically movable top-gate was analyzed by the team of researchers proving high potential for wide industrial application [32]. This type of sensor can be integrated into many processes as a mean of quality control, or in the product to enhance its longevity or features.
Many quality instructions or even standards require certain type and level of illumination for visual control areas. Widely used lighting solution is LED, but even though very efficient devices, LEDs dissipate some of the energy through heat [33]. This heat is then being conducted to the soldered joints and can cause malfunction, flickering, or even delamination of the joint [33]. An integrated microsensor for real-time measurement of temperature in the area of the soldered joint was presented and proved capable [33]. This sensor can detect changes in the temperature of the surface mounted LEDs and engage the control unit to act accordingly. When the temperature is higher, thermal resistance is higher so the efficiency of the unit decreases.

This microsensor can be used in many industrial equipment monitoring or maintenance systems. It could be also applied to many different types of products to improve product quality, energy efficiency and durability.
Micro and nano scale devices can also harvest energy [34]. Small devices based on the piezo-electric effect, capable of energy harvesting and sensing, are multifunctional, durable, and reliable [34], [35]. Triboelectric nanogenerators could provide energy harvesting, power themselves, sense and monitor environment changes, and interact with the environment [34], [35]. These self-powered devices are currently mostly used in medicine for drugs distribution, cell removal or bacteria and cancer cells killing. This technology is fairly new and a lot of advances are to be expected. There would be many industrial applications for micro and nano motors/robots in health and safety, maintenance, security and quality control. Applications in these areas are yet to be seen.

5. CONCLUSION

Research reviewed in this paper has shown that, although the industrial application of micro and nano technologies (MNTs) in the communication and monitoring processes is still relatively new, there is a great potential. Advances in technologies, Big Data, artificial intelligence (AI), Industrial Internet of Things (IIoT) create necessity for multifunctional, small, reliable, and inexpensive sensors. Combining MNT sensing, Big Data analytics and artificial intelligence can provide game changing systems for monitoring and controlling in terms of production, maintenance, health and safety, and quality control processes.
Fiber-optic sensors are widely used and commercialized components in areas like: large civil engineering structures, quantitative chemical processes, health and safety monitoring of composite materials and structural health monitoring. Optic systems are superior to metallic copper conductors when comparing: data transfer speed and quality, infrastructure longevity, attenuation level, electromagnetic wave interference and many more.
Optical fiber, micro, and nano-enabled sensors are highly capable of providing precise, real time, measurements and sensing of: different gasses, pH value, moisture content, humidity, shape changes, strain, acoustics, temperature, pressure, vibration characteristics, voltage, current, flow distribution, ions, and many more. Micro and nano enabled devices are also capable of energy harvesting from renewable sources, such as: wind, vibration, solar, light and sound. Micro and nano motors can harvest energy for the self-powering, but they can also interact with their environment and power up other components. Micro and nano motors have been proven capable to realise different advanced tasks such as: drug distribution in human body, bad cells removal, killing bacteria and cancer cells, and much more. Different focused research in high advanced areas like bioengineering also pointed out that similar concept can be successfully applied in traditional manufacturing industries as well.
The advantage of MNT-based sensors is that once they are developed they can be applied in almost every possible industrial sector, for wider purposes, like quality control. There are strong indications that future research should be focused on retrofitting older industrial equipment to Industry 4.0 by utilizing micro and nano sensors and components, for improved maintenance, quality control, production management, process parameters monitoring, and more through AI predictive systems that uses MNTs.

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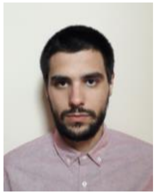

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