Original scientific paper

Role of Sensors in the Paradigm of Industry 4.0 and IIoT

Andrei A. Porokhnya and Ilia U. Yakimenko

Abstract **—The purpose of this article is to review new trends in monitoring the condition of oil on all factory area processes. New solutions are being introduced into this industry with new advantages in the development of artificial intelligence, as well as machine learning and sensor technologies, which are applicable for data-based maintenance. They are called predictive maintenance. This paradigm is going to replace the old one. It changes the traditional routine preventive maintenance scheme and provides a deep understanding of the equipment performance [1]. Monitoring and checkout of conditions are necessary to maintain in a real-time environment because on-line control of equipment status can put down an operating cost, by eliminating the need for equipment outage for everyday diagnostics. The analysis based on oil samples is an effective tribotechnical systems approach for early diagnosis of failures, as it contains valuable information about the process of degradation of oil and the state of tribotechnical pairs [2]. But there are some problems with this method. The first is the way of oil sampling. There are lots of mistakes that may be made during the oil sampling process, and they can affect the results. The second is a delivery to laboratory which complicates the diagnostic process. That's why we cannot say this approach is an on-line method of diagnostics. For the better prognosis of pending machinery failure one needs to know a real-time correlation between size, shapes, and concentration of wear debris parts [3].**

***Keywords* — hydraulic fluids, lubricating oils, maintenance, operating conditions, sensors.**

I. Introduction

THERE is nothing new in the process of fluid management and monitoring. It was an important part of the industrial boost that took place in the 1960 decade [4]. But the way of management of fluid conditions is still manual and oil sampling process still has a few fundamental problems. Logistic chains, a delivery process and achievement of the results are still the major problem and the main disadvantages of this method. Owing to the place where an oil sample was taken, we can obtain the best oil results. The thorough process is recommended to avoid erroneous results. For the best one, the oil sample must be taken from the ports according to the approved procedure defined by each OEM manufacturer. When we take an oil sample, we have the engine run for a few minutes at medium rpm at a normal oil operating temperature to get a homogeneous sample. The ingress of atmospheric pollution can affect the composition of soil samples, and leakage from the oil sampling bottle can reduce the volume required for testing. The delay in sampling of the oil before it enters the laboratory should be minimal. It is also important to calculate the results and respond to them as soon as possible, as some cases of contamination can be catastrophic. It is very important to determine when to take an oil sample and observe the trend. The autonomous measurement methods, including spectrographic and ferrographic methods, are still the most useful strategy for diagnostics of conditions of tribotechnical systems). As a fact, tribology contribution to the Industry 4.0 is very important, too. Tribological studies have a direct or indirect impact on the technologies. This relationship can be expressed under the term "Tribology 4.0" [5], [6]. Tribology takes the fundamental role in engineering services and it is involved in developing the prediction of the maintenance life of such components as bearings [7], in diagnostic analysis and forecasts of the ageing life of fluids [8], in the study of failure mechanisms of existing equipment [9]. Operational monitoring of lubricants in machines is important to increase the service life of lubricated components. Wear debris in the lubricant is measured in real time, for example, by ferrous wear debris sensor with permanent magnetic is described in the next chapter [10]. Vibration analysis is often used to diagnose malfunctions of machines containing rolling bearings and gears [11], [12], [13]. It includes augmented reality, cyber physical systems, cloud industry and internet connection to develop tribology in all previously mentioned fields. The factory process requests sensor systems which can answer their needs and be a real-life complete solution. These all were wire analog sensors, the golden age of them lasted for three decades until 2005. In view of Industry 4.0 it was the first step of sensors to give all information in a wireless way and the ability to remove connection restrictions. Industry 4.0 has been started since 2000 as a new Paradigm.

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Andrei A. Porokhnya is with the North Caucasus Federal University, 1 Pushkin str., 355017, Stavropol, Russian Federation (e-mail: aporokhnia@ncfu.ru).

Corr. Author Ilia U. Yakimenko is with North Caucasus Federal University, 1 Pushkin str., 355017, Stavropol, Russian Federation (e-mail: y@kimenko.ru).

Industrial internet, Industry 4.0 or Industrial Internet of Things (IIoT) are the drivers of industrial revolution. It has already started by the impact of cost-effective manufacturing. Advanced computing, cost-effective sensing, data analytics are making the next great step in Industry 4.0 [2]. All these transformations were enabled by the internet and gave us lots of solutions within the new Industry 4.0. Paradigm [14]. There are giants of the process automation. Companies, such as Siemens, General Electric, Schneider Electric, Bosch, etc. have made lots of efforts to deliver all reducing cost technologies to the market and to the customer [15]. In the end of these processes the business became fully digital with cloud services, big data analytics and smart sensing. These are important technologies in the new industrial revolution [16]. Now lots of companies connect customer industrial equipment with sensor architecture, offering on-line monitoring and analysis to cars, vehicles, industrial robots, or equipment, such as compressors or different types of agricultural equipment. Other manufacturers make a shift to generate new sensor technologies on their own Industry 4.0 platform. Such a kind of technologies gives us much more information in view of connectivity, integrability, and flexibility. The main role in the IIoT or the Industry 4.0 Paradigm is played by sensors. The large part of them is a portfolio of smart sensors for a fluid diagnostic. The product family includes pressure, fluid level or temperature sensing, and oil conditional sensors. The collaboration of these sensors with a proper software solution and ethernet opens to the customer the world of data which is working in real time and enabling them to manage their equipment and optimize their productivity. In this context, the article describes a methodology for developing smart sensors for industrial fluids, different steps, approaches, and considerations. The focus mentioned in view of developing Industry 4.0 or IIoT is collecting and exchanging data across all fields of a factory process area. Data is generated with the help of a large portfolio of sensors. Different types of parameters are measured by these sensors. They offer information about certain parameters. Such a kind of sensors are called real-time or in-line sensors. Given that, there are two kinds of fluids in the factory process area. The first type of liquid is a fluid as the product for customer and the second is the main part of the operational process. If company monitors the parameters of the fluids from the second group, factory controls all functionalities of the process to prevent an outage and failures. The same holds for the fluids from the first group, a plant ought to maximize the quality of the product. In this case there is a dual Paradigm of Industry 4.0 - on the one hand it is a part of a Statistical Process, on the other hand it's a part of conditional monitoring approach.

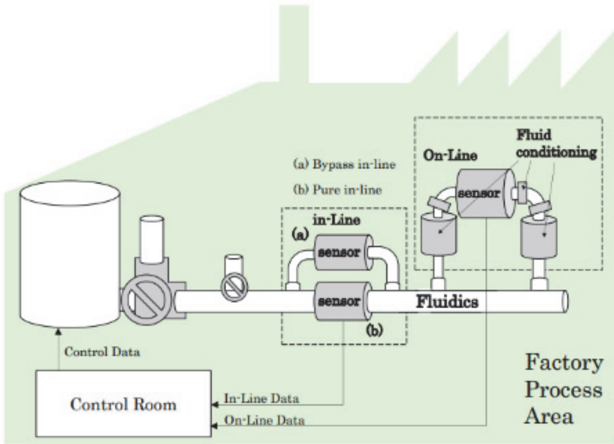

Fig. 1. Schematic overview of sensors within a factory process area [17].

II. Materials and Methods

The main purpose of this article is to compare different types of sensors for monitoring of liquids in the context of information content. The main task is to identify the main advantages and disadvantages that are necessary for the further development of the real-time remote monitoring system in the Industry 4.0 paradigm by comparing systems which were already used. The research is based on information about the oil conditional sensors for on-line and in-line monitoring. On-line sensors installed in the lubricant system of the equipment control are continuously circulating flow in the one place during the operation. Although these methods can provide detailed information about the oil ageing process. In addition, this method cannot provide real-time machine health information that could be used to prevent instantaneous failure of components during operation and provide a forecast of a waiting fault. On-line sensors that can perform the analysis of the lubricating oil in real time without the need for complex configuration and qualified analysts are very much in demand now. It is necessary to study a new sensor structure and an extended measurement cycle in order to increase throughput without compromising sensitivity. New challenges in view of fluid management and monitoring become stronger bearing in mind ecology, reducing of owing cost and predictive management. Analogue sensors or sensors based on the control of a limited number of parameters cannot solve these problems ang give perfect results. A number of methodologies have been approved since wear debris changes the oil's permittivity, optical properties permeability and conductivity. By monitoring the presence, size, shape, and concentration of debris we can maintain equipment properly (Table 1). Some of the on-line sensors reviewed in the sections are already commercialized, other on-line sensors, such as the microfluidic capacitance sensor are tested in a bench-top experimental setup. Certain equipment generates small debris particles even in proper working conditions.

TABLE 1. A SUMMARY OF THE WEAR DEBRIS SENSORS

Monitoring method		Advantages	Disadvantarges
Inductance	Magnetic collection	Can work in a high flow of fluidic, cleaning an oil from ferrous debris	Cannot detect individual debris particles and nonferrous debris particles
Capacistance	Dielectric constant	Differentiate ferrous and nonferrous debris	Extremely low sensitivity and throughput capability
Ultrasonic	Acoustic amplitude change	Detect solid debris and air bubbles	cannot differentiate metallic and nonmetallic debris
	Integrated ultrasonic and inductive pulse sensor	Differentiate ferrous, nonferrous, solid debris and air bubbles	Low throughput,
Optical	Wear debris morphology	Detect debris particle shape and material	Low throughput, complicated system

A. Ferrous wear debris sensor with the permanent magnetic

Wear debris can be divided into three parts: ferrous, non-ferrous, and ceramic debris. It is a ferrous debris because the largest part of engine components is made of steel. Therefore, a number and a size of ferrous wear debris are the main sources of information during the engine operation.

The simplest sensor used in detecting the ferrous debris was invented by Gill company and was called Gill Sensor. This type of sensors was developed to detect ferrous debris in lubricating oil. There are two identical sensor units, each of them consisting of permanent magnet and sensing coil. Permanent magnet works in two ways. The first, it collects ferrous debris to the sensor tip, and it is able to determinate ferrous parts. The second, it prevents oil circulation system from wear debris travelling and can reduce further damage of the system. It is the main advantage of this system.

Structure of the wear debris sensor base on bulk measurement is shown in Fig. 2. Therefore, real time diagnostics cannot be provided by such a kind of sensors in the context of debris particles' size and concentration, additionally, non-ferrous wear debris cannot be detected by such a kind of sensor to prevent emergency outage.

B. Capacitive method and ferrous wear debris sensor

A sensor based on capacitive method in non-conductive lubricating oil was invented to detect and to count individual wear particles and micro metallic debris, as a microfluidic device. Structure of such a kind of sensor is shown in Fig. 3. This device consists of a single channel for fluid flow and an inlet to a reservoir. Channel has dimensions of 40 μm (H) × 100 μm (W) × 300 μm (L) and a pair of coplanar electrodes. Electrodes are placed in the channel with a gap of 40 μm. Electrodes have the capacitance change during a ferrous debris runs through the microfluidic channel. Change capacitance is detected by the pair of coplanar electrodes as a difference between the capacitance of non-conductive lubricating oil and the capacitance of non-conductive lubricating oil with micro metallic debris mix.

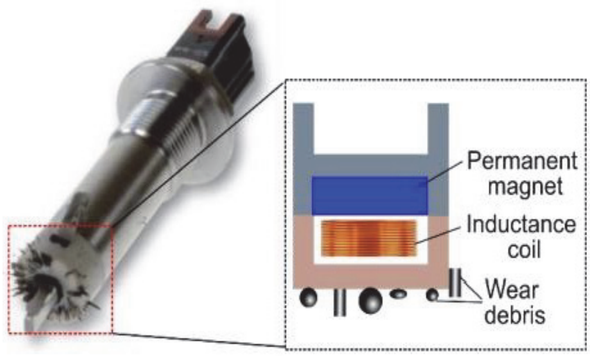

Fig. 2. Schematic structure of a ferrous debris sensor with the permanent magnetic.

That's why this type of sensor can detect and measure ferrous wear debris from 10 μm to 25 μm. The main advantage is that this range of parameters can help in diagnostics and can find abnormal wear in the equipment. But this device has disadvantages. The first is that small single wear particles from non-ferrous metals cannot be detected by such a sensor, and it cannot perform diagnostics in real time to prevent emergency outage. The second, the capacitance of oil is changing during engine operation because the acid number content and viscosity influence it. That's why the change of the capacitance detected by the pair of coplanar electrodes is changing too. It is difficult to determine the dependence. The third, the size of wear debris parts is limited by the size of the microchannel. If oversized particles try to pass through the channel, there will be the effect of bridging and jamming. Therefore, the capability of this type of sensors for real time monitoring and diagnostics is limited by these disadvantages.

C. Ferrous wear debris sensor with permanent magnetic

The main issue of sensors of real time monitoring is to classify ferrous and non-ferrous wear debris and split up the influence of changing lubricant oil capacity from water droplets and air bubbles. The 3D solenoid coil was used to solve challengers. The structure and the main working principle is shown in Fig. 4. [18]. Two factors can change inductance of this sensor. The first factor, the non-ferrous metallic particles are present in lubricating oil in the magnetic field. The total magnetic flux decreases, the same happens with the coil's equivalent inductance, therefore an eddy current is induced inside the debris to oppose the existing magnetic field.

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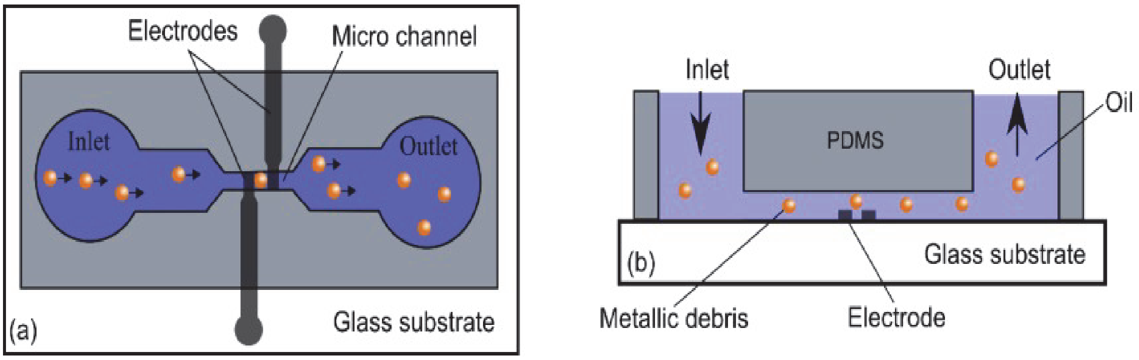

Fig. 3. Schematic structure of a ferrous debris sensor based on capacitive method with microfluidic channel (a) - top view, (b) – side view [19].

The coils' inductance is decreased by the passage of a non-ferrous debris particle because of the dominance of the eddy current effect at higher frequencies. The second factor is that if ferrous wear debris particles are present in lubricating oil in the magnetic field the coil's equivalent inductance is increased. The induced eddy current is small at low frequencies, coils' inductance and total magnetic flux increased by ferrous debris in the oil.

An air bubble cannot be the issue for inductance change, because the permeability of air (1.0000037) is like oil (~1.0) the electrical conductivity of air is approximately 10-21 times that of metallic debris, The eddy current effects are negligible. And it is the same for water [20]. Therefore, it is critical to provide real time monitoring and health checks of the engine and warnings of abnormal operation. The next problem, multiple small wear debris most likely identified as one debris particle when they are passing through the sensing area. It will look like a machine failure.

As shown in Fig. 4, black lines are the magnetic flux, red lines are eddy current generated magnetic flux. The main issue for this type of sensors is non-ability to detect debris below 100 µm, because such a solenoid structure is difficult to detect individual particles.

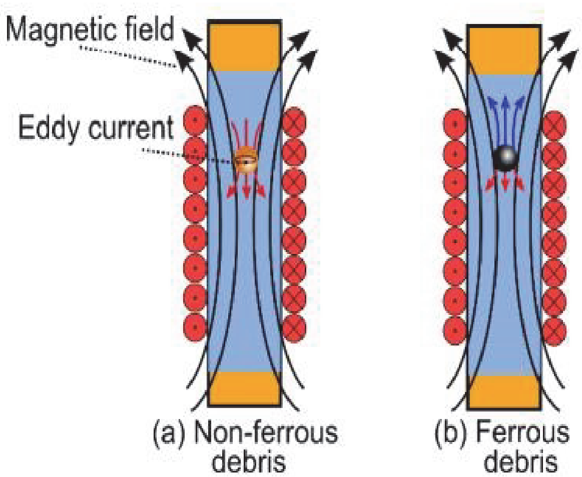

Fig. 4. Illustration of the sensing mechanism for inductive sensors.

A. *Wear debris sensors based on acoustic method*

The acoustic detection method is capable to detect debris particles and ignore air bubbles and water droplet in the flow stream. Acoustic detection method is based on the echo signal amplitude and uses single or dual ultrasonic transducers. If there is a large amplitude of echo, the larger debris size will be detected. The echo is generated by the wear debris particle in the oil flow steam, then it reflects the acoustic pulse. For an air bubble it will be negative, and it will be positive for wear debris.

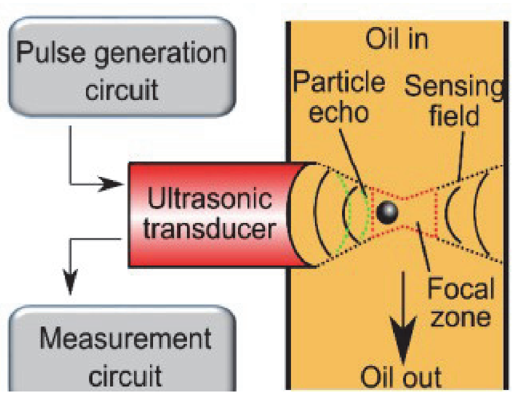

Fig. 5. Illustration of a single transducer ultrasonic sensor.

Therefore, positive and negative peaks value give information about air bubbles and solid wear debris, but they cannot differentiate ferrous debris from non-ferrous or dielectric wear debris, because all solid particles have similar reflection. Another problem of this method is that it cannot give exact form information about the number and size of wear debris particles [21]. Combinations of an ultrasonic and an inductive pulse sensor were invented to overcome these challengers. Solid debris is detected and counted by ultrasonic pulse sensors while ferrous and non-ferrous debris are detected by inductive pulse sensor. Flow recess structure was invented to force all debris particles to go through the focal zone.

The inductive sensor is made of 2-layer flat coils wound on a glass tube with a diameter of 1 mm; the ultrasonic pulse sensor uses a spherically focused ultrasonic transducer to generate a focused beam and receive reflected acoustic echo [20].

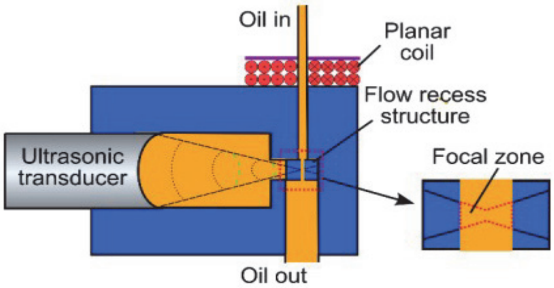

Fig. 6. Schematic of the inductive-ultrasonic integrated wear debris sensor.

B. Wear debris sensors based on optical methods

Different technologies based on light transmission measurement have been developed during the last 10 years [22]. Mostly these were microscopy and lase scattering. One of the first systems which was developed to detect wear debris in lubricating oil using microscopy and imagine systems were the webcam-based wear debris sensor developed by Hamilton et al.

Such a kind of sensors consists of a high-speed camera, which constantly takes a high-speed shooting of oil. A light source helps camera to find out wear debris in the flow channel [23]. The property of the oil to transmit light changes when wear particles are present in the lubricating oil, and the number of particles can be measured by measuring light transmission. MATLAB helps to get information about the size of wear particles and shape information, which helps in the process of identifying worn components and preventing an emergency shutdown. Although, there are some problems with using these methods. The main problem is errors in the calculation of wear particles, and then determining their size. An additional problem is to have a high-quality image from a high-speed camera.

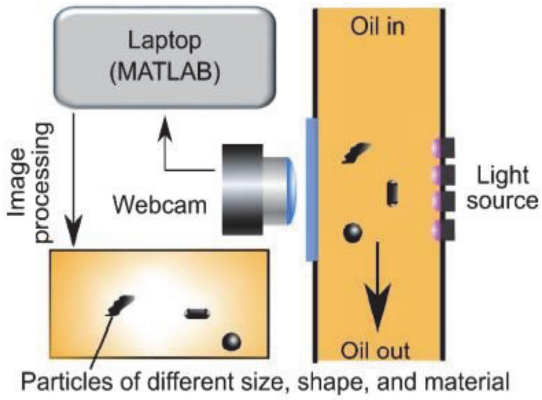

Fig. 7. Schematic of the webcam-based wear debris sensor.

Optical methods allow noninvasively assessing the microstructure, functions, and composition of liquids, as well as ensuring reliable operation when working in the field. In addition, the digital electronics revolution has significantly reduced both the price and the size of components (sensors, light sources, computing units) that are critical for most optical systems. The integration of such optical components with compact microfluidic, micromechanical, and inexpensive electronic and communication systems makes it possible to create reliable photonic intelligent sensor systems that are inexpensive, scalable, and ready for implementation in Industry 4.0.

III. Results

The main advantages and disadvantages are described in Table 1. This table makes it easy to realize that modern oil conditional sensors for on-line monitoring in real time do not cover all the needs of the Industry 4.0 paradigm. The two main problems are low throughput and low sensitivity. Considering that these sensors are designed to cover the needs for detecting wear elements, it is impossible to say that they are suitable for modern standards. Of all the sensors now, optical sensors, that are used as a modern solution, win, and we can say the development of new sensor technologies lies in this key.

They are unusable and are an integral part of the Industry 4.0 paradigm. Modern online technologies for these functions either have low responsiveness or have a high error rate due to low selectivity. Potential solutions may be the development of a) a highly selective sensitive method that responds only to specified characteristics; b) online and miniature portable sensors based on elemental analysis approaches, such as the Fourier transform infrared spectroscopy (FTIR). Processes such as combined spectroscopy are the main advantages in the field of liquid monitoring, especially due to their resistance to water molecules. However, the high efficiency of query annoyance, the low level of identification and the precise optical tolerance hinder the development of cheap and integrated technical solutions and expand the limitations of the proposed methodological methods. The main factor limiting the overall and long-term autonomy of embedded sensors is the stability of optical sensors under constant exposure to severe operating conditions. Considering these requirements, the new type of sensors should include solutions such as self-calibration, microcontrollers and protective coating. On the other hand, these solutions should have low cost, improved performance, wireless connectivity, and compact dimensions.

IV. Discussion

The paradigm of process fluid management and monitoring has evolved in the previous decade. It is driven by a necessity for improving the process quality, efficiency, and safety of products. Provided that factory area process is fostering new methods to control different types of parameters from basic to complete chemicals and physical fingerprints [24].

A very important aspect here is data security. The main question is who owns the data and who has the right to access certain data, as well as how security considerations are respected. The Industry 4.0 has essential component controlled based in a complex manufacturing process: while the factory collects data, their interpretation belongs to the sensor manufacturer. Perhaps the most difficult aspect of the introduction of Industry 4.0 is the inaccessibility of the enterprise to criminals and unscrupulous competitors. On-line integration will create great risks of information leakage. Cyberattacks on enterprises and even a cyber threat is possible. Such a large-scale problem will cost manufacturers a lot of money and may negatively affect their reputation in the eyes of consumers. The only solution is private and collaborative research in the field of data encryption. In the conditions of the Industry 4.0, safety becomes not only a problem for manufacturers, but also an important aspect for the customer. The collection and analysis of data from the consumer – and the company will need it for its development – can be perceived as a to privacy from the point of view of customers. [25]. The transparent environment necessary for business will find its expression in the consumer sphere.

Another disadvantage of that system is issues in the operation of devices, computing, and software. Unstable communication or an incorrectly configured service network can reel the stability of technologies. For continuity of work, it is necessary to consider all possible difficulties with configurations and networks. Wireless sensors are a prerequisite for Industry 4.0. However, there are many challenges to ensure secure communication. One of the attacks is denial of service [26]. Wormhole is another threat to wireless sensors, the blockchain methodology proposed in the handbook is used to ensure the security of communication channels in Industry 4.0. Industry 4.0 requires a reliable one that allows direct communication between machine [27], [28]. 5G provides communication support for Industry 4.0 and provides a long battery life. In view of 5G network, there is a problem of resource allocation for network users. Therefore, network slicing is required to distribute the network across N sensors [29], since there may be several sensors in the factory using the same network to transmit and share the information. This increases network traffic, which also leads to latency or data loss. which should be effectively retransmitted [30]. If we talk about operational failures and, as a result, production downtime, it is necessary to monitor and analyze the operating condition of the network in a timely manner and eliminate the slightest anomalies. Thus, only constant monitoring will help to cope with threats.

Bearing in mind now challengers in a factory process area and new paradigm of the Industry 4.0 and the IIoT principles of building sensors architecture must be changed. Standard interfaces, auto calibrations and settings, communications and full set on-board algorithms must be included into a new smart sensor concept description.

V. Conclusion

Three main reasons to develop the process in the field of a new kind of sensors bearing in mind a new paradigm of the Industry 4.0 and the IIoT:

- providing the integration of complicated main dimension methods and increasing the autonomy of developed sensors
- reducing sensors' maintenance costs and calibration needs and increasing operation life
- offering equipment to supply hardware-independent solution.

With the development of these types of sensors, it is possible to obtain a large number of advantages. First of all, this is a real control of the oil condition at any time from the oil change to the next oil change in the service interval. This will give constant access to the technical condition of the equipment. It will reduce the reliance on repair costs and the time of failure detection. The development of proper sensor portfolio pretenses a new organization and technical challenge in numerous fields of industry. Real-time monitoring of the fluid condition is an effective tool in the practice of equipment maintenance. Combined with the Internet of Things, machine learning and laboratory analysis, it can play a vital role in detecting fluid anomalies before catastrophic events and unplanned downtime. Although real-time monitoring may not be as comprehensive as traditional laboratory analysis, it more than makes up for the shortcomings by providing fast and continuous scanning of the fluid state to allow the end user to make timely decisions. All in all, sensor product developers need tools to integrate these new components without changing OEM data, for example, machine vision algorithms. Therefore, the development method must also consider this necessary hardware agnosticism to ensure rapid migration to newer platforms. Therefore, meeting the expectations of the Industry 4.0 will only be possible if, apart from the sensor measurement principle, a full set of on–board algorithms, communications, standard interfaces, auto calibrations, etc. are included within the sensor system itself. From the side to the addition of intelligence levels, connectivity, etc. fluid sensors include various physical and chemical parameters in their range of sensitivity sensors. Fluidics sensors are gradually turning into full-fledged integrated mini-laboratories capable of measuring specific chemicals, pollutants, the presence of particles, oxidation, uniformity of samples, etc. that their motorization in real time is very relevant and even critical for several industrial processes.

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