ROLE OF IN-PROCESS METROLOGY IN INDUSTRY 4.0 SMART MANUFACTURING

Robiul Islam RUBEL 1,*, Md. Hasan ALI 2, and Md. Washim AKRAM 3

1 Department of Agriculture and Biosystem Engineering, South Dakota State University, Brookings, SD, USA
2 Department of Industrial Engineering, Dalhousie University, Halifax, Nova Scotia, Canada
3 Department of Mechanical Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

*E-mail: rubel.ruet10@gmail.com
E-mail: hasankuet38@gmail.com
E-mail: washime1ruet@gmail.com

ABSTRACT: Industry 4.0 is an idea of manufacturing by hybridizing the knowledge of all aspects of branches and using it to optimize and quality products. It is replacing old manufacturing models and concepts basis on the new hypothesis and gradually being implemented in the establishment. The metrological standards, measurement methods, and equipment have also been updated with the smart idea of the new manufacturing systems in Industry 4.0. Metrological methods and equipment are integrated with a lot of productions lines of smart manufacturing to increase the production rate, reduce time, and guarantee production quality from metrological standpoints. Since Industry 4.0 smart manufacturing tends to incorporate big data in the production line to monitor and control the production system, a continuous real-time monitoring system can help accelerate smart manufacturing. In-process metrology is such a feedback control system for real-time monitoring of the data in productions using smart sensors and actuators. Since Industry 4.0 covers not only manufacturing but also other different aspects, the role of in-process metrology is out of notice, not debated too much though important. This paper has put an attempt to discuss and highlight in-process metrology for Industry 4.0 smart manufacturing. The technology and challenges for in-process measurement in Industry 4.0 have also been studied.

KEYWORDS: In-process measurement, Smart manufacturing, Industry 4.0

1. INTRODUCTION

Between the era of 1700~1800 AD, the first industrial revolution happens where manufacturing was evolved from focusing on manual labor performed by people with the aid of domestic animals [1]. Later these periods come with a few impressive innovations like water and steam-powered engines and different types of machine tools to improvise the work. The industries turn out to speed production with the innovation of electricity in the 20th century called the second industrial revolution [2]. Computer and electronic devices accelerated the growth and production in the manufacturing line with a more controlled and precise way of delivering as online feedback was used to control the production line [3-5]. The old method of measurement is no more effective in this era of smart manufacturing. So, the metrological concept has shifted to get more feedback information that is the main breakthrough for securing quality and fast production in smart manufacturing of the Industry 4.0 hypothesis [6-7]. Industry 4.0 or IoT or sometimes called smart manufacturing is a big concept of integrating production, management, operations with the aid of smart digital technologies (Fig. 1) [6-10]. With the advancement of technologies and versatile application of aspects like Cyber-Physical Systems, Artificial Intelligence, Big Data, Cloud Computing, Blockchain, etc. manufacturing companies are transforming to intelligent enterprises [4,6,9].

![Fig. 1. Concept of Industry 4.0 [12]](image-url)
Industry 4.0 promises greater interoperability, information exchange, and integration, to produce the best product with limited resources with the highest satisfaction. Smart sensors and metrology for precise test and measurement are essential for these advanced systems in Industry 4.0 [4,6,9]. Where in-process measurement represents the concept of measuring the workpiece or products dimension during processing. The processing may be involved in any machining processes like milling, grinding, turning, drilling so on. The measurement may be done by any tactile, non-tactile sensors. In-process measurement helps the manufacturer to control the product dimension instantly when any process is ongoing. If a proper feedback mechanism is integrated with the measurement system, the production line can be guided to make improved quality outputs [11].

To ensure process reliability during manufacturing, feedback control systems with in-process measurement sensors automatically compensate for any dimensional and tolerance variations, which can arise for example, when turning equipment gets worn over time or due to rotating speed eccentricity or the result of temperature fluctuations [4,11]. In such turning cases, the in-process control systems will monitor the measured values in real-time, will give a controlling action to the turning process continuously until the nominal dimension has been reached. This in-process measurement and control help to minimize part rejection and necessary rework in any kind of manufacturing industry. This kind of feedback control achievable by in-process measurement is the backbone of the Industry 4.0 hypothesis. The linkage between the in-process measurement in Industry 4.0 lies in the use of data resources for smart manufacturing. Precision control of the manufacturing process is a key of the modern manufacturing process to maintain the quality of the product, checking tolerances and performance of the product even before its ready for use [4,6,11,13].

In-process measurement can check the shape, size, fittings for the parts being made in the industry. Industry 4.0 implement the command to the production machine using the data resources collected from market evaluation, customer reviews, technical points of view, and so on. The same data can be put into the feedback control system device any production line and make customized and quality products in smart manufacturing [7]. Linking the in-process feedback control with the machining process will reduce the chance of product defects that is the way to control modern manufacturing in Industry 4.0. Though a big part of Industry 4.0, in-process metrology is overlooked [6,13].

Fig. 2. Concept of smart manufacturing

Peoples think it is just an improvement over time being fail to understand the significance of the real field. An example can be drawn using robotics in our modern life, but never do we think that how it is making things easy for us. Fig. 2 shows the simplified concept of smart manufacturing. This manuscript has intended to describe the principle of the Industry 4.0 hypothesis on the metrological ground and what factors and technologies waiting for use to us in the interconnectivity of the productions. Associated merits and forgoing challenges to overcome also outline to put forward.

2. LITERATURE REVIEW

One key principle for the manufacturers to do must is to consider accuracy, precision, reliability, cost, speed, and measurement. Different methods are available in the manufacturing process to carry out the measurement. Even for an easy and simple manufactured product, there is more to inspect than meets the naked eye. The metrological requirements vary across the industry sectors. Large volume production usually relies on a sampling inspection strategy [14]. For example, cell phone component producers typically measure a few parts from each lot or batch to ensure metrological consistency. On the other hand, in highly sensitive and critical applications, parts are 100% inspected. Such as in aerospace industries, manufacturers usually inspect each part independently and keep records for the items in long term. As Industry 4.0 is one of the ways to takeover, metrology is becoming more complex than ever. In-process metrology hypothesis called backbone for Industry 4.0 has made it more sophisticated. Non-contact measurement likely optical and laser systems and automated robotics are some means of Industry 4.0 metrological systems that are well known to us [4,6]. It is unthinkable now to measure anything in the industry without modern technologies since they are being an integral part of
the future development of smart industries [8,15]. Everyone seeks more and more efficient manufacturing systems and customized products, and metrology plays as a booster to customer satisfaction in this case.

Metrology’s function in digitized factories is to endlessly collect and share data through interconnected modules, machines units, production lines to support at every stage. Manufacturers must grow their products under the shade of the metrological data to achieve the objectives of Industry 4.0. This creates a place for in-process measurement giving the manufacturers better visibility of the processes, supply chain, and performance. The use of sensors, robotics, 3D imaging is boosting in all sectors and metrology cannot stay away from accepting and using it. The advantages of speedy verification and feedback kick off all the drawbacks of in-process metrology in the way of automated manufacturing. There is an increasing demand for in-process metrology applied in a digitized mode in factories and production lines. In the industry 4.0 concept, customized product is an extended mode of business and in-process metrology is a turnover factor in it the quick supply of the products. W. Gao et al. [16] explained in-process metrology as a way of precision measurement and quality assurance. They have discussed different methods and the importance of in-process measurement in microfabrication industries. T. Kalsoom et al. [17] noted Industry 4.0 as a vigorous improvement of manufacturing and accumulated the technologies that are being used for metrology of this field. They have classified different sensors and actuators with their relative advantage and disadvantages in general terms. These articles lack information about the functionality of the sensors and actuators in Industry 4.0. R. Y. Zhong et al. [8] classified Industry 4.0 as intelligent manufacturing, Internet of Things (IoT), enabled manufacturing, and cloud manufacturing, where each concept is pretty close to each other through the hypothesis has some discrepancies [7,10].

Y. Takaya et al. [17] exposed in-process measurement as a strategic tool for Industry 4.0 in science, engineering, measurement, manufacturing, business, society economy, etc. There is always an increasing demand for high-precision parts. So, the concept of tactics now is a strategy in the 21st century for holistic measurement approaches. R. Y. Zhong et al. [8] provided a framework about Industry 4.0 in their article. Though they did not make any comments about in-process monitoring, the framework mentions the term ‘Real-time control and monitoring that is analogous to in-process metrology. Y. J. Qu et al. [9] have the same kind of framework and have a separate section for real-time monitoring. With these examples, metrology has been found included in every framework and a major part for sure but out of attention generally.

3. IN-PROCESS METROLOGY

In-process measurement is understood as a metrology of automatic measurements executed during the manufacturing process. In-process measurement systems are included in the manufacturing process to get automatic feedback [15]. Typically, offline measurements necessitate the products to be measured and removed from the production process or production line [18-19]. Then inspect the product as a discrete operation, with inspected parts either returned to their next production operation, discarded, or identified as finished inspected parts. The problem is that it creates a repositioning error [20-21]. In-process measurement is out of this problem and no error occurs due to repositioning or change of axis [15]. In-process measurement is also real-time feedback to act instantaneously on smart manufacturing. The components of the in-process measurement are placed such as sensors and measurements probes are integrated with the line flow-through system to allow continuous monitors of product parameters passing through the measuring station [11].

The basic parameters measured to provide feedback are the size (height (h), wide (b), depth (t)), roundness (R), curves (S), angles (θ), finishes (Δh), etc (Fig. 3). The function of the feedback becomes the function of the corresponding measure quantities. Thus, the feedback response can be presented as a function of the stated parameters like- Feedback = f(h, b, t, R, S, θ, Δh).

![Fig. 3 Schematic of in-process measurement](image_url)
Inspecting the manufacturing process by an in-process measurement system will make the feedback system capable of measuring shape and dimension to judge the product conformance.

4. IN-PROCESS METROLOGY IN INDUSTRY 4.0

Industry 4.0 smart manufacturing is defined as fully automated, all system integrated, and collaborative manufacturing systems. Smart manufacturing reacts in real-time to meet changing demands based on big data involved and conditions them in the smart production lines according to the customer needs and supply chain management. Since manufacturing businesses, manufacturing companies, and even manufacturing processes are in full transformation. Therefore, measurement in Industry 4.0 is expected to be reliable to receive feedback from the data source. The requirement stands mainly due to the increasing number of automation cycles, digitalization of equipment and monitoring systems, less personal involvement, the linking of digital and physical environments.

In-process measurement here works a little bit different way to feedback from the data source that is also received instantaneously during manufacturing. For example, consider the measurement parts of the smart manufacturing system where the metrological department works under the quality control system. This department employs measurement technology to make the decision of the quality and expectations about a product. Measurement technology has also some back-and-forth processes to take part in decision making by sensing elements and data analysis. If we break down these two components of the system, it flows as the blocked flow chart as presented (Fig. 4).

5. TECHNOLOGY FOR IN-PROCESS METROLOGY IN INDUSTRY 4.0

Measurement in old days was based on physical contact sensors and actuators. These imply sensing a process in an off-line mode that was later moved as an on-machine measurement mode. On-machine measurement is better than the off-line measurement process but still consists of the problems of stopping the process line [16]. Later innovation of sensors especially non-tactile sensors facilitates the metrologies to rethink the measurement process and set it up as a non-human interference automated sensing technique complying Industry 4.0 hypothesis [17]. Technology for in-process metrology is also sensors (adaptive or proximity) and actuators but mostly non-tactile [17]. Tactile sensors were reliable and served for a long time and can be applicable for in-process gauging with limited applications. But over time it wears out quickly and most cases are not applicable for in-process due to the essential physical contact needed between the sensing tips and objects. Examples are laser tracker, displacement gauge, force sensor, fast tool servo, atomic force microscope, etc [16-17,22].

Non-tactile sensors are superior in these perspectives and do not interfere with the process line and are just adopted and installed for most modern manufacture. However, they have been reported to have very fragile performance. Typical sensors of non-tactile probes are laser triangulation sensor, confocal probe, electrostatic force microscope, captive sensor, etc. Most manufacturers now looking to automate the process and quality control metrology in their industry to handle inspection tasks more efficiently and profitably [14]. Sensors in smart manufacturing would perform the programmed measurement task.

Fig. 4 In-process metrology in Industry 4.0 for a feedback mechanism
Sensors do data processing, data analysis, comparison, and rework determination of the measured result, within its integral processing unit. Therefore, it can negate the need to communicate raw data back to the operator or a central processing unit. However, the Industry 4.0 big data should be loaded in the in-process measurement unit to provide its autonomous control power of monitoring. Limitless sensors are now being produced for industries ever before to record and optimize the production lines. In-process sensors are being applied in the production line to take the dimensions, finishes, tolerances, quality, records, feedback, and comparisons [11]. Research is projected to create a more elaborate environment for the human to automate transformation for Industry 4.0. For example, European Union (EU) is funding a multi-partner project called “SYMPLEXITY” to research and improve on humans and robots collaborating in metrology for easier the Industry 4.0 transformation.

6. CHALLENGES FOR IN-PROCESS METROLOGY

For the upcoming Industry 4.0 ready for production spreading worldwide means that metrology system also needed to competeugradation switching from the present status to the newest and speediest status maintaining the necessary production protocols. Since Industry 4.0 is not a unified system for a single point rather a cooperatives system between different units, companies, and countries, thus the protocols must also interpolate amount the of stakeholders sharing the same resources. All standards and protocols should speak the same things to reduce the chance of conflicts and verities. Smart factories in Industry 4.0 thus must be equipped with advanced-prediction tools and instruments to collect and process the data can accumulated from a systematic process [10,23].

(a) In-process measurement for Industry 4.0 is a data-driven concept and modern process. The measuring technologies involving this idea are the newest and precise instruments. The skills required for operating and analysis and decision making when human intervention wanted to undergo expertise labor sources. The cost associated with hiring numerous observers is reduced in the automated metrological concept though maintenance raises the cost at a high level. Under this circumstance, low production capacity cannot supersede the housing cost of In-process measurement with Industry 4.0 standards.

(b) Companies are always competing for for-profit and production. They want to reach more and more customers and widen the business scope. That builds up a gap between the companies for metrology integration. The old days was the age for physical division and competition that is now being transformed as the digital gap in term of integrity, security, connectivity. The practice of hiding the patents and merits of products resist the business owner to share the data bank amongst the companies unless the government forcefully implements so. Companies are barely positive to form a single source of data that provides all information for manufacturing, planning, sourcing, and inspections [14]. Each company deems protecting its intellectual property, maintaining statistical protocol, and considering information from another source as an element of the digital thread. Sister concerns are likely to fit to overcome these circumstances as long they gain their benefits. The government can fit some common goal for the sack of humanity on which all companies and bodies can come together to share all data.

(c) The expertise and focus for different bodies based on the location, laws, labor laws, protocols, etc. that also push down the interconnectivity of Industry 4.0. One major key issue for digital data sharing even agreed is the nature of data and file format. In in-process metrology software directly supports, reads, and writes files to the data bank and source it back when desired. Bridging among the data sources, data formats, machine and probes version, language, and units are a great hindrance. Backdated software, compatibility, languages, and units might cause a key issue in synchronizing that is not easy to solve even today.

(d) Manufacturer targets human satisfaction to make a profit. Human satisfaction and appeal are complex issues and matters of huge research and analysis. Culture, religion, locations, weather, etc. are the indications for human satisfaction. Truly, Industry 4.0 has a chance to build connectivity to get the ideal product for each customer. However, from a metrological perspective, implementation is not that easy. Point to point analysis towards satisfaction is difficult to achieve. In-process metrologies suffer the same to satisfy humans.

(e) Though we are talking about in-process metrology as fully automated in Industry 4.0, human involvement is still required. Reducing human observers can cause havoc not only for a single company rather for a group of companies because of the shared data bank. Analysis and integrity of the data based on the human requirements and converting them into manufacturing terms need human always.

(f) The quick blooming change of industries from the traditional labor-intensive process to fully automated and digitalized steps cause a lot of labor
jobless. This can lead to unemployment and social instability. If laborers lost their skills, the system cannot be reversed as quickly the digitalization is occurring. Unemployed people will be engaged with evils as the map of profession and demand will change [24-25]. The concern on it and the raising labor problem no more an issue of a problem if there is enough scope to ensure the employment rate for a community.

7. CONCLUSIONS

This brier review has compiled the prospect and challenges of the in-process metrology for Industry 4.0. The present era of smart manufacturing is going to take over the place of existing manufacturing systems surely. The success now will be counted on how smartly the policymaker can accommodate the shifting. The metrological concept found through this study mentioned that the challenges do not lie on the materialistic approaches only, a social and psychological matter also closely associated with it. Cyber risk and big data management will be a cruciate issue.

8. REFERENCES


