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Integrated and Intelligent Manufacturing: Perspectives and Enablers

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ABSTRACT

With ever-increasing market competition and advances in technology, more and more countries are prioritizing advanced manufacturing technology as their top priority for economic growth. Germany announced the Industry 4.0 strategy in 2013. The US government launched the Advanced Manufacturing Partnership (AMP) in 2011 and the National Network for Manufacturing Innovation (NNMI) in 2014. Most recently, the Manufacturing USA initiative was officially rolled out to further "leverage existing resources... to nurture manufacturing innovation and accelerate commercialization" by fostering close collaboration between industry, academia, and government partners. In 2015, the Chinese government officially published a 10-year plan and roadmap toward manufacturing: Made in China 2025. In all these national initiatives, the core technology development and implementation is in the area of advanced manufacturing systems. A new manufacturing paradigm is emerging, which can be characterized by two unique features: integrated manufacturing and intelligent manufacturing. This trend is in line with the progress of industrial revolutions, in which higher efficiency in production systems is being continuously pursued. To this end, 10 major technologies can be identified for the new manufacturing paradigm. This paper describes the rationales and needs for integrated and intelligent manufacturing (i^{2}M) systems. Related technologies from different fields are also described. In particular, key technological enablers, such as the Internet of Things and Services (IoTS), cyber-physical systems (CPSs), and cloud computing are discussed. Challenges are addressed with applications that are based on commercially available platforms such as General Electric (GE)'s Predix and PTC's ThingWorx.

1. Introduction

It is well-known that manufacturing is the most important resource for today's wealth-generating process. Manufacturing is a critical element of economic growth in all regions. With the introduction of the concept of Industry 4.0 by Germany, there has recently been a great emphasis in advancing manufacturing technologies around the world, in developed and developing countries. This advance is being achieved by joint effort between government and private sectors, and through the close collaboration of industry and academia. It has spearheaded a strong movement toward a brighter manufacturing future.

This paper provides a study of the manufacturing technology trend and of the two unique features of integrated manufacturing and intelligent manufacturing. Aspects of the technical enablers for advanced manufacturing systems are described, and potential future directions and challenges are discussed.

1.1. The Fourth Industrial Revolution

Looking at the historical advancement of manufacturing system technology, three fundamental measurements are often used: quality, productivity, and cost. These three critical measurements are both related to each other and integrated together. However, early industrial revolutions focused more on the measurement of productivity than on the other two measurements. In other words, manufacturing productivity and efficiency are the focal points for manufacturing technology advancement, while quality and cost are

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the constraints. In this circumstance, the question of how to improve the productivity and efficiency of manufacturing systems has been the critical issue in industrial revolutions.

Fig. 1 depicts the progress and characteristics of the industrial revolutions. During the First Industrial Revolution, with the introduction of Walter's steam engine technology at the end of the 18th century, the method of production was changed from manual craftsmanship to mechanical production, leading to a great improvement in productivity. In the Second Industrial Revolution, with the introduction of electrical power and the transfer line, pioneered by Henry Ford at the beginning of the 20th century, high-speed mass production became the standard manufacturing practice. As a result, productivity was significantly improved and reached a whole new level. During the Third Industrial Revolution, manufacturing efficiency and productivity have been further enhanced by the combination of information technology (IT) and automation systems, such as flexible manufacturing systems (FMSs) and robotic technology. Now, as we consider ourselves to be experiencing the dawn of the Fourth Industrial Revolution, the Internet and smart devices are being widely used to further improve the productivity and flexibility of manufacturing systems.

1.2. Manufacturing initiatives in different regions

In 2013, Germany unveiled its Industry 4.0 strategy, which directed a great deal of global attention to the advances in manufacturing systems technology [1]. In the United States, the government launched the Advanced Manufacturing Partnership (AMP) in 2011. Since then, many other initiatives have been rolled out, including the Advanced Manufacturing Partnership Steering Committee "2.0" in 2013; the National Network for Manufacturing Innovation (NNMI) in 2014; and the Revitalize American Manufacturing and Innovation Act, which was signed into law by the President of the United States in December 2014 [2]. Most recently, Manufacturing USA was officially launched by the US government in order to further "leverage existing resources... to nurture manufacturing innovation and accelerate commercialization" by fostering close collaboration between industry, academia, and government partners [3]. In 2015, the Chinese government officially published a 10-year plan and roadmap toward manufacturing: Made in China 2025 [4]. The largest international collaborative program, Intelligent Manufacturing Systems (IMS), which is led by Japan, is also rolling out a roadmap for its next step with its IMS2020 project.

2. A new paradigm: Integrated and intelligent manufacturing

Among the many features characterizing today's modern manufacturing system technology, such as lean, virtual, and rapid-response systems, two features stand out and are sure to be carried over into the next generation of manufacturing: integrated manufacturing and intelligent manufacturing. As shown in Fig. 2, the market and process demands have driven technology from an information-intensive focus to a knowledge-intensive paradigm, in which big data analytics and knowledge bases play an important role in the current manufacturing environment.

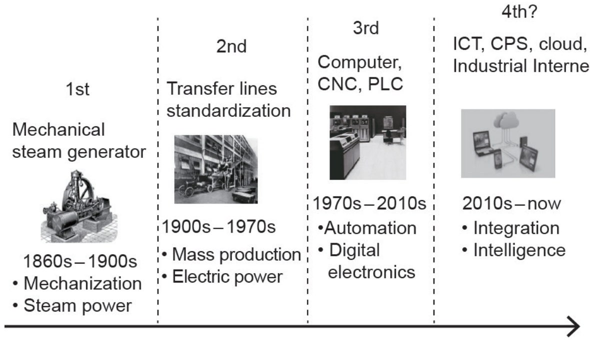

Fig. 1. The progress and characteristics of industrial revolutions. CNC: computer numerical controller; PLC: programmable logic controller; ICT: information and communications technology; CPS: cyber-physical system.

The evolution of integrated and intelligent manufacturing (i^{2}M) technology is driven not only by the market demand, but also by technological advances. There are 10 major technologies that can be identified as the key elements of the new manufacturing paradigm. As shown in Fig. 3, these technologies include six supporting elements: three-dimensional (3D) printing or additive manufacturing, robotic automation, advanced materials, virtual or augmented reality, the Industrial Internet, and cyber-physical systems (CPSs). They also include four foundational elements: big data analytics, cloud computing, applications, and mobile devices. The ways in which these elements impact advanced manufacturing systems and, more specifically, how they affect i^{2}M, are described in the following sections.

2.1. Integrated manufacturing

The introduction of the concept of manufacturing systems began with advances in digital computing capability in the 1960s; at that point, some kind of integration started to emerge within manufacturing. Under this scenario, the machines and devices in a manufacturing process are no longer isolated. Rather, they are parts of a system, and all the components can be effectively coordinated in order to achieve improved productivities. For example, the computer-integrated manufacturing system (CIMS) has been widely adopted by companies.

The Internet of Things (IoT) and CPS technologies opened the door for tremendous opportunities in advancing such integration to a whole new level, making integration wider, deeper, and more open. As a result, manufacturing system controls are no longer limited to dealing with physical things and devices such as materials and machines; they are now able to process a large range of data, information, and knowledge in real time. This processing is realized by three levels of integration in manufacturing: vertical integration, horizontal integration, and end-to-end integration [1].

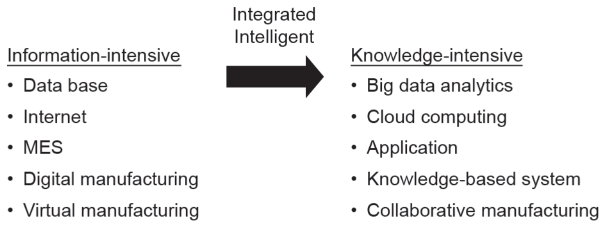

Fig. 2. The new trend in manufacturing systems. MES: manufacturing execution system.

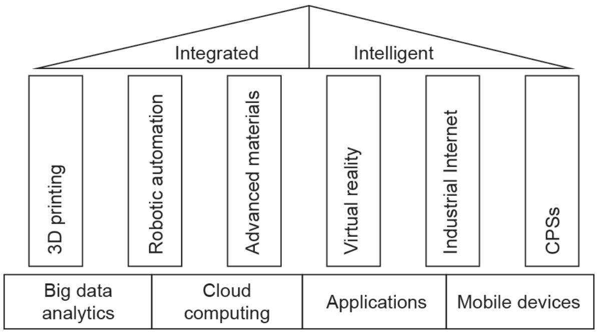

Fig. 3. Ten major technologies for i^{2}M.

2.1.1. Vertical integration

Vertical integration addresses the issue of seamless connectivity among all the elements that are included in the product life cycle within an organization. Activities in marketing, design, engineering, production, and sales are all closely integrated. Technologies such as the manufacturing execution system (MES) and computer-aided process planning (CAPP) can thus be better utilized in order to support information and knowledge sharing within the organization. In this way, resources within the company—including but not limited to information, data, capital, and human resources—can be used more effectively and efficiently.

2.1.2. Horizontal integration

Horizontal integration occurs when a company is closely integrated with its suppliers and partners. Modern industry has already adopted supply-chain management technology, such that a horizontal value network has been established in many industry sectors. However, challenges still exist in terms of efficiency, intellectual property protection, the establishment of common standards, knowledge sharing, and so forth. With the implementation of an advanced knowledge base and an Industrial Internet, those barriers can potentially be removed. A common knowledge network platform with practical protocols and standards is needed in order to further enhance the effectiveness and quality of horizontal integration.

2.1.3. End-to-end integration

End-to-end integration is probably the most active area in the new age of manufacturing. Firstly, on the factory floor, machine-to-machine integration is provided so that machines are truly an integral part of the manufacturing system. Secondly, it is now feasible to integrate customers into the manufacturing system, thus allowing engineers to obtain feedback from customers easily and in a timely manner. Thirdly, product-to-service integration is feasible, allowing the condition of the product in use to be directly monitored by the manufacturer. In this way, the value chain will be extended to the customer service of the product.

2.2. Intelligent manufacturing

Due to the increased complexity of modern manufacturing systems—particularly after all the units/elements been integrated into a common system—process decisions have become much more difficult. There is a strong need to leverage vast amounts of manufacturing data and to utilize the power of computing intelligence to enhance the decision-making process in manufacturing.

Intelligent capability refers to three functions, which operate in an analogy of a human body: sensing, decision-making, and action. With today's rapid advances in sensing and control technologies, there is no lack of sensors or actuators in manufacturing systems. The challenge is how to process information and knowledge so that the right decision can automatically be made by a computer at the right time and in the right location, with little or no human intervention. New technologies are emerging in this areas, such as big data analytics, machine learning (ML), and cloud computing, which provide great potential for enhanced intelligent capability in manufacturing.

2.2.1. Big data analytics

Big data analytics is becoming a critical component of today's IoT environment. It refers to the process of extracting information and knowledge from big data by uncovering hidden clusters and correlations, so that systematic patterns can be recognized and a better decision can be made. A tremendous amount of data is available throughout the manufacturing process today, from machines, production, logistics, and user feedbacks. These data were typically unavailable or did not exist in the traditional manufacturing environment, so conventional analysts cannot deal with such large amounts of data. New procedures and schemes are being developed in big data analysis, such as correlation and clustering, statistical modeling, and cognitive ML. With big data analytics, it is feasible to use only relevant and core information from terabytes or more of datasets in manufacturing, and the right decision can be made effectively. With this approach, the control of manufacturing systems will shift from reactive decision-making to proactive decision-making. Due to its great potential for manufacturing applications, big data analytics is gaining ground and becoming more and more important for advanced manufacturing systems.

2.2.2. Machine learning

One of the key characteristics of human intelligence is the capability to learn. ML refers to the computer's capability to understand and learn the inside of a physical system through computing algorithms based on data. Data mining, statistical pattern-recognition algorithms, and artificial neuron networks (ANNs) are some examples of ML methods. For manufacturing systems, the implementation of an ML algorithm makes it feasible for a machine or other device to learn its baseline and working conditions automatically. It is also feasible to create and upgrade a knowledge base throughout the manufacturing process.

2.2.3. Cloud computing

Cloud computing provides an Internet-based computing service, which makes it possible to share software so that a user does not have to install the needed software locally. This practice is often called "software as a service" (SaaS). For manufacturing system implantations, however, sharing software through the Internet is no longer enough. It is also necessary to share information and knowledge in such a way as to create a marketplace for software and knowledge sharing. This practice is called "platform as a service" (PaaS). Efforts are being made to develop and implement PaaSs for manufacturing applications.

It can be foreseen that in the near future, with the advancement of intelligent manufacturing technology, data and information will be collected in real time by well-equipped sensors and transducers from all areas in the product life cycle. The data will then be processed through cloud computing, and accurate decisions can be made continuously and autonomously with little or no human intervention. As pointed out in Ref. [5], a new manufacturing platform—cloud manufacturing—is feasible by "combining with the emerged technologies such as cloud computing, the Internet of Things, service-oriented technologies and high performance computing." An efficient manufacturing eco-environment is emerging as integration and intelligence become the two hallmarks of a new manufacturing paradigm.

3. Technology enablers

3.1. The Internet of Things

The term "IoT" was first introduced by the British entrepreneur Kevin Ashton in 1999 while he was working on a global network of radio-frequency identification (RFID)-connected objects. Today, with the rapid development of Internet technology, many physical objects can be connected via the Internet through embedded electronics, software, sensors, and network devices. This has been further expanded to non-physical systems, such as service or social elements. Therefore, IoT is also referred to as the Internet of Things and Services (IoTS).

For i^{2}M systems, the IoT provides a unique and much-needed foundation that is capable of connecting all the elements of a manufacturing system together. In this way, not only can the efficiency of data collection be improved, but the quality of the data can also be significantly improved. The IoT also enables network control and the management of manufacturing equipment, assets, and information flow.

Leading IT companies are providing network hardware and software support for the implementation of intelligent manufacturing systems. For example, Cisco provides the following product and services: network connectivity, fog computing, security, data analytics, and automation [6].

3.2. The cyber-physical system

The CPS is a system of collaborating computational elements and controlling physical entities. It refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities [7]. Many CPS devices have been developed and used in industries, including the aerospace, automotive, energy, healthcare, and manufacturing industries. This generation is often regarded as embedded systems. In fact, CPS forms the backbone of IoT implementation.

Embedded devices are objects that have special sensing and computing capabilities. They are the critical elements in Industrial Internet implementation. With these devices, it is feasible to process data at the local level so that useful information or abstracted data are communicated through the network. In this way, communication efficiency can be significantly improved.

Current embedded devices have limited computation capabilities. A new generation of smart embedded devices is being developed for many applications. In a manufacturing process, smart embedded devices, such as the Watchdog Agent™, are capable of not only collecting data, but also processing the data so that certain decisions can be made fast and locally. More and more of these smart embedded devices will be adopted in manufacturing systems for intelligent decision-making.

A fully fledged CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices. Attention has been paid to its connectivity and to the intelligence mechanics of computational intelligence. Mobile CPS has emerged with advances in cloud computing and wireless sensing technologies. Security and reliability are two critical requirements and challenges of mobile CPS. Long-distance and global mobile CPS are yet to come.

3.3. Industrial Internet

As mentioned earlier, the IoT provides the foundation for cloud computing and makes SaaS and PaaS feasible. However, for manufacturing applications, an industry-hardened IoT is needed to provide the reliability and security that are required by industry. To this end, an industry consortium initiated by General Electric (GE) is developing Internet technology for industry, resulting in a special IoT system for industrial application: the Industrial Internet of Things (IIoT).

The IIoT refers to the integration and connectivity of complex physical machines and devices, humans, and resources through networked sensors and software for the purposes of industry production and operations. As stated by GE: "By taking advantage of the rapid explosion of sensors, ultra-low cost connectivity, and data storage together with powerful analytics (commonly referred to as IIoT…) these value-added services can produce business outcomes for customers and produce incremental revenue for the company" [8]. The term IIoT was first introduced by Frost and Sullivan around the turn of this century. At that time, the Industrial Internet, which is the fundamental tool for the implementation of IIoT, was used as a collective toolset for a digital enterprise transformation. Today, this term is often used along with other terms, such as the IoT, Industry 4.0, big data, ML, and machine-to-machine communication. It is a core strategy in the United States to provide the critical capability for the next industrial revolution: IT-connected machines, people, and resources.

Other than regular Internet applications, such as office automation, the Industrial Internet requires conditions such as a hardened environment on the factory floor and extreme dependence on its reliability. For example, factory floor equipment must tolerate a wider range of temperature, vibration, electrical interference, and humidity, along with frequent interruptions. In addition, the Industrial Internet must be compatible with various physical devices, such as machines, robots, conveyors, testing equipment, and tooling equipment. Due to the evolution of the technology and equipment on most factory floors, the IIoT must be able to work with modern and legacy equipment and protocols. It also requires a high level of security in the face of possible intrusion from both the inside and outside of the plant.

To address these challenges, industry-hardened industrial networks have been developed that often use network switches to segment a large system into logical sub-networks, divided by address, protocol, or application. Systematic logical control and firewall systems are also used when it becomes necessary to connect to an office automation network for the vertical and horizontal integration of the enterprise.

To facilitate the implementation of the IIoT for effective industry applications, GE recently announced its software solution: the Predix Cloud [9]. The core capability of the Predix software system is to capture data out of large manufacturing or industrial operations and to perform analytics on them.

4. Industrial practices and implementations

4.1. Emerging technology trends in manufacturing

In the continued push to realize Industry 4.0 capability, many manufacturers have recognized that the adoption of new technology trends is necessary for their businesses. At the end of last year, *Manufacturing News* predicted five emerging technology trends for i^{2}M systems. These are: cybersecurity, advanced materials, 3D printing, predictive analytics, and collaborative robots [10].

4.1.1. Cybersecurity

With advances in network technology, and particularly in the mobile network system, individual privacy and company security continue to be critical issues—not only for information protection, but also (and more importantly) for the safety of advanced manufacturing systems.

An increasing number of companies are developing and implementing internal cybersecurity systems. To enhance industrial cybersecurity, the US government is developing the necessary technology and legal protection. The US National Institute of Standards and Technology has established a cybersecurity framework in order to share best practices and technologies to allow industry to effectively address the security issue. Cybersecurity will remain the top priority for many companies as they prepare for Industry 4.0 implementation.

4.1.2. Advanced materials

New and improved materials are much needed for modern products and manufacturing. Carbon fiber has been rapidly adopted by the industry for its improved material properties and reduced weight. Carbon nanotube manufacturing has shown impressive improvement in recent years.

There are significant needs in high-tech areas as well, such as needs for new materials for batteries and 3D printing. Desirable characteristics of new materials include energy storage capability, a light weight, information-processing capability, a smart memory, and so forth.

4.1.3. 3D printing

New additive manufacturing systems and materials have improved greatly in recent years, and their growth will continue in the future. Additive manufacturing holds great potential for further improvement in production efficiency, as well as in product design and development processes. With the availability of new materials and with improvements in the accuracy of 3D printing machines, more and more industries will embrace this technology for their production. It has been forecast that this may be the year in which manufacturers start to adopt 3D printing on a large scale. In fact, some industries, such as the aerospace and hospital industries, have already begun producing critical components using 3D printing technologies.

4.1.4. Predictive analytics

Predictive analytics is probably the most successful and promising application of big data technology for industrial applications today. Manufacturing companies have realized that a tremendous amount of data is available throughout their manufacturing systems, and is either being wasted or insufficiently utilized. To remedy this deficiency, predictive analytics may well be the most promising solution. Many companies are racing to develop learning and analysis algorithms for effective and practical analytics that can yield future predictions of machine or equipment conditions. In this way, maintenance can be performed more efficiently and equipment down time can be reduced significantly.

4.1.5. Collaborative robots

Collaborative robots provide a unique benefit to manufacturing systems: their capability to work with human operators. This capability makes robot systems flexible and smart in dealing with complex and challenging material-handling and manufacturing situations. Robots are no longer viewed as standalone machines that are separate from human interactions. An increasing number of robots will be used in manufacturing for improved automation and reduced cost. To this end, collaborative robotics technology is being rapidly developed and implemented.

4.2. Intelligent manufacturing platforms

In order to implement intelligent manufacturing technology, industries are preparing to develop cloud computing platforms based on IIoT. It has been estimated that investment in IIoT is expected to reach $60 trillion in the next 15 years. By 2020, it is predicted that more than 50 billion devices will be connected to the Internet. In order to unleash the benefits of IIoT for industrial applications, many software platforms are being developed and deployed, such as the aforementioned Predix platform by GE.

A significant feature of all such platforms is the capability to build “digital twins.” A digital twin is a computerized model of a physical device or system that represents all functional features and links with the working elements. A digital twin is more than a virtual computer system for simulation study. It provides the operation status, insights, outcomes, and knowledge that are associated with the proper functions of the physical system. A digital twin is capable of communicating with the physical system it represents via real-time sensing devices, so as to keep it almost synchronized with the real-time status, working condition, position, and environment situation. Digital twins allow for the prediction of future conditions.

4.2.1. GE: Predix

GE’s Predix is a comprehensive, purpose-build industrial platform for the implementation of intelligent systems to monitor and control physical devices or systems through the Industrial Internet [9]. As shown in Fig. 4 [9], the key elements in Predix include the Predix Edge, Predix Cloud, and Predix Machines. An edge-to-cloud deployment model is used in Predix, which differs from other public cloud-only models. This architecture is suitable for many industrial applications.

Predix was developed based on GE’s own practice. In its early years, GE had a need to build digital twins for the operation monitoring and control of machines such as turbines. For this purpose, GE developed twins and edges, and used them successfully through the Industrial Internet. GE then opened the platform to the public so that original equipment manufacturers (OEMs) and third-party developers could build twin virtual models for various systems.

The core in the Predix is its Cloud Foundry, which provides an open-source PaaS. It has a unique microservices architecture, which supports many existing languages and programming tools. Using

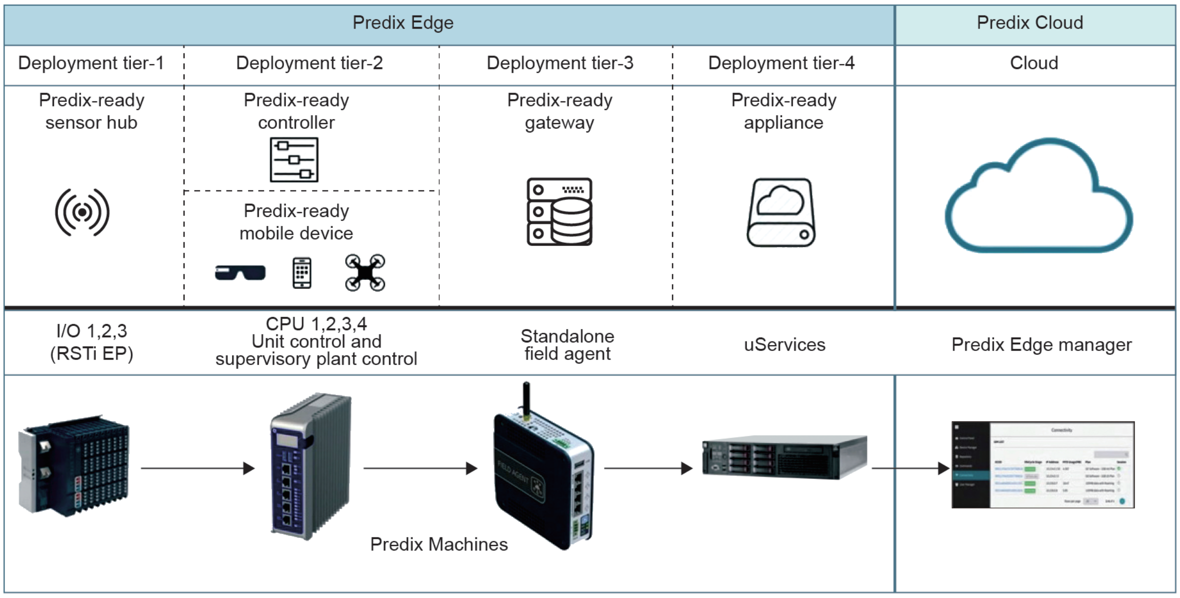

Fig. 4. The Predix platform [9]. CPU: central processing unit.

its modern development-and-operations (DevOps) environment, third-party developers, and particularly app developers, can quickly build, test, and implement scalable systems for various industrial applications. There are currently more than 500 000 twins and applications using this platform.

In Predix, industrial data are collected from manufacturing processes in unprecedented volumes, which are almost impossible for the public cloud to handle. In addition, Predix provides an industry-specific intelligent analytic service to help companies process, analyze, and make decisions about their manufacturing status. With such capability in place, it is possible for a company to make real-time decisions that can dramatically improve the business operation of the enterprise.

Typical applications of Predix include:
- Scheduling and logistics
- Connected products
- Intelligent environments
- Field-force management
- Industrial analytics
- Asset performance
- Application performance management (APM)
- Operations optimization

It should be pointed out that there is still a long way to go in the development and deployment of the Pridex platform. It is still in the early stages, and its applications are largely in the processes of monitoring and diagnostic decision-making. Its analytic capability is still very limited. Its artificial intelligence (AI) and deep learning algorithms need to be further enhanced.

Recently, GE announced a collaborative program with China Telecom to provide the Predix service to customers in China. This development will certainly have a significant impact on the advance of intelligent manufacturing technologies in the largest manufacturing base in the world.

4.2.2. Siemens: Product life-cycle management and the smart factory

The smart factory is the leading concept in Germany's Industry 4.0 strategy. There are two levels of smart factory technology. The first level focuses on the shop floor, where all production devices will be fully integrated by wired or wireless communication systems. Individual machines or devices will no longer be isolated. A fully automated MES will be deployed with various types of sensors, transducers, and device controllers. Data and information can be collected in real time at various locations regarding device statuses, working conditions, environmental parameters (i.e., temperature or humidity), and so forth. This information will be readily available to human or system control for the monitoring, prediction, and control of the manufacturing systems.

As a result, the shop floor will be much more smart and flexible. There is even a push to make end-to-end, machine-to-machine communication a reality. To this end, many sensing and signal-processing technologies, including smart image processing and recognition, are being developed and implemented on the factory floor. In the future, it will be feasible to have each machine, or even each product, carry a chip that stores all relevant information for effective communication. It is feasible that when a product arrives at a location, the product's chip will transmit the process information to a machine so that appropriate processing preparation and execution can be performed without human intervention.

At the second level of smart factory technology, a smart factory comes with a fully digitized factory model (i.e., a digital twin) for a production system. The digital twin is completely connected to the corporate product life-cycle management (PLM) system with sensors, controllers, programmable logic controllers (PLCs), computer numerical controllers (CNCs), supervisory control and data acquisition (SCADA) systems, and other communication devices. The factory floor conditions of a system will be immediately reflected by its digital twin, for the effective monitoring, prediction, and control of current and future events.

To facilitate communication between the digital twins, Siemens rolled out the Intosite software platform. This is a cloud-based application for sharing digital manufacturing and production information in a 3D context [11]. It provides smart map navigation of virtual factories in various locations, and enables collaboration through the sharing of the same manufacturing data by engineers and managers at different locations.

With this software smart factory platform, a cloud-based manufacturing operational management (MOM) system can be implemented, through which data and information from the factory floor are updated in real time and are readily available, should a decision regarding the process need to be made. All changes on the factory floor can also be uploaded automatically to other IT systems, such as the PLM repository, with the Siemens PLM software: Teamcenter. In this way, the efficiency and productivity of a manufacturing system will be significantly improved. Siemens's Fusion system attempts to support the IIoT platform, and could be used for manufacturing implementation.

However, Siemens' smart-factory-based technology requires extensive integration of the software platform with the factory floor systems. This system should also be more closely integrated with predictive analytics for further enhancement of its intelligent manufacturing decision process.

4.2.3. PTC: ThingWorx

In 2014, PTC acquired ThingWorx and further developed it into a major IIoT platform by integrating it with PTC's Internet-based PLM program. ThingWorx is now playing a major role in the implementation of intelligent manufacturing technology. It is a well-developed platform with several elements, including ThingWorx Studio, ThingWorx Analytics, ThingWorx Utilities, and ThingWorx Industrial Connectivity. As illustrated in Fig. 5 [12], all these elements work with the central piece: the ThingWorx Foundation.

The ThingWorx Foundation provides connections to all the ThingWorx components, with end-to-end security technology. It enables users to connect, create, and deploy industry-specific applications throughout the IoT system. Among the components included in ThingWorx, three fundamental functions are provided: Core, Connection Services, and Edge.

The ThingWorx platform was developed based on a ground-up and model-drive approach. Many graphic drag-and-drop tools have been developed and are available for the end user to use to construct specific applications; this makes its application relatively easy and convenient. Since it is one of the earliest platforms for IoT application for industries, there are many user-friendly tools and algorithms available for analysis and data presentation. Some of the tools are also used by other platforms, such as Pridex.

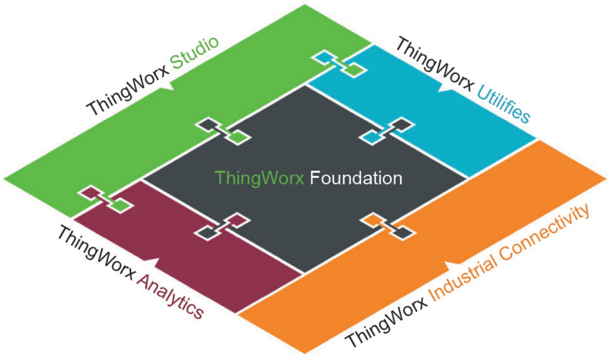

Fig. 5. The ThingWorx platform [12].

4.3. Predictive analytics for intelligent manufacturing

In the development of intelligent manufacturing technology, effective predictive analytics is probably the most important element for the practical implementation of such technology. In all PaaSs, major efforts are devoted to building effective analytics for decision-making. In recent years, many leading computer software and hardware providers, such as IBM, Microsoft, Intel, and Google, are gearing up their efforts to develop analytics technology. Advances in analytics technologies will have a significant impact on intelligent manufacturing implementation.

4.3.1. IBM: Predictive analytics

IBM has a long history of providing software tools for industrial applications. In 2010, IBM rolled out a specific predictive analytics service platform: SPSS Predictive Analytics Enterprise. This platform aims at providing deep descriptive and predictive analytics for various industrial applications, including manufacturing, healthcare, and administration management. As a single solution, it can work with all types of data, whether structured or unstructured, or in numerical or graphic formats. It also includes some processing tools with the capability for statistical data analysis, data mining, and ML. It will be very interesting to see how manufacturers can benefit from another powerful IBM knowledge-building engine: IBM Watson Analytics.

IBM claims that the SPSS Predictive Analytics Enterprise can provide the following capabilities and benefits [13]:

- Descriptive and inference statistical analysis;
- Predictive modeling and advanced algorithms for numerical, text, and graphic data formats;
- The capability for interactive visual and plain-language presentations of data and information;
- A framework for secure and automatic data collection and management; and
- Real-time scoring for the predictive control of company assets.

4.3.2. Microsoft Azure: Machine learning and predictive analytics

Microsoft offers a collection of integrated cloud services through its Azure framework [14]. In this framework, certain ML and predictive analytics tools are provided. As illustrated in Fig. 6 [14], the user can create an ML application by selecting a set of read-to-use algorithms in the ML studio. The application can then be deployed through an Internet-connected processor, such as a PC, in order to build a predictive model for specific applications.

Other elements in the Azure framework that can be used for data processing and intelligent decision-making include HDInsight and R Server. With Microsoft Azure HDInsight and Microsoft R language, HDInsight clusters can be created in Azure so that users or R programmers can select a particular algorithm or method to build practical analytics.

At this time, the majority of applications of Microsoft Azure is in the commercial and service sectors, such as for the management of web services. However, these analytics tools should be employable in manufacturing areas in the future.

4.3.3. Intel: Nervana™ AI Academy

The computer hardware giant Intel is also aggressively developing its AI capability to provide ML and predictive analytics for various industrial applications. This is being done through the framework of Nervana™ AI Academy [15].

Nervana is a platform that is specifically for machine deep learning, based on its Nervana neon™ and Nervana Engine technologies. The Nervana Engine uses a new memory technology called high-bandwidth memory that is both high capacity and high speed, and is therefore particularly good at addressing the vast amount of data in today's typical industrial environment. Nervana neon™ is a high-level programming language that is used for deep learning programs. With the integration of Intel's next-generation processor, Nervana provides a powerful AI platform with processing and built-in networking that has unprecedented speed and scalability. Intel claims that all form of data, including numerical or non-numerical data such as natural language and graphics, can be processed in this platform.

4.3.4. Google: Cloud ML Platform

Google has been developing AI and deep ML technology for a long time. It provides a cloud-based ML service through its Google Cloud ML Platform. This net-based ML algorithm has excellent performance and accuracy. The uniqueness of the Google AI platform include its powerful text analysis, speech recognition, and image analysis capabilities

In order to enhance industrial applications, Google recently added a new component to its ML platform: TensorFlow. This is an open-source software library for data processing with a data flow graph structure. In the data flow graph, nodes represent mathematical operations, while edges represent multidimensional data arrays. This framework can process a vast amount of data and information well, for a situation with high levels of uncertainty. This technology can be implemented in manufacturing, where high levels of uncertainty are always a reality.

4.4. Challenges

With all these promising advances in manufacturing systems technology, significant challenges still exist, mainly in the following areas: legacy IT infrastructure, standardization, knowledge base, and closed-loop control.

4.4.1. Legacy IT infrastructure

In many companies, IT infrastructures were basically developed

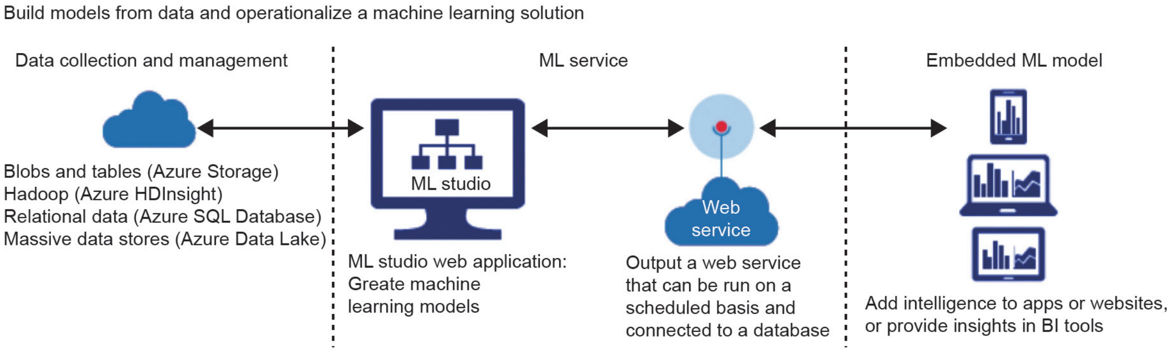

Fig. 6. The Azure ML workflow [14]. SQL: structured query language; BI: business intelligence.

as communication networks linking different data or information pools. Although this is efficient for limited data handling, it is becoming more and more difficult to deal with vast amounts of data and information across different manufacturing platforms. In particular, there is a significant security challenge when adopting a powerful cloud computing platform. Legacy IT infrastructure must be reevaluated or replaced for the new manufacturing paradigm.

4.4.2. Standardization

Standardization is necessary in order to integrate different elements in manufacturing systems, including both hardware and software. At the device level, communication input/output and protocols must be standardized for efficient and secure data transfer. This is particularly critical for end-to-end integration. At the platform level, interfaces between software modules must be standardized so that the potential of computational intelligence can be fully utilized.

4.4.3. Knowledge base

The availability of an effective knowledge base is still the bottleneck in the implementation of intelligent manufacturing technology. Although ML techniques have been adopted for the construction of knowledge bases from data, significant challenges remain due to the high levels of uncertainty in the manufacturing environment. Based on the open structure of several IIoT platforms, such as GE's Predix, many parties are working together to build a knowledge base; however, a practical and effective knowledge base that is capable of manufacturing monitoring and control is yet to be developed.

4.4.4. Closed-loop control

Predictive analytics has been playing a significant role in intelligent manufacturing. However, its implementation and impact on the factory floor is still very limited. The link between analytics and actuation must be closed so that a truly intelligent closed-loop control strategy can be implemented in the next generation of intelligent manufacturing. To this end, both hardware and software innovations are urgently needed for the development of cloud manufacturing platforms.

5. Conclusion

A new industrial revolution is on the horizon, led by manufacturing revitalization and advances, which can be characterized as the i^2M system. In many countries, governmental and private sectors are working closely together to upgrade the manufacturing base and improve market shares.

The core breakthrough in i^2M technology is in the area of the complete integration of information and communication technology with modern manufacturing systems. To this end, advanced CPS and IIoT technologies, together with big data and cloud computing, are playing significant roles in the shift into a new manufacturing paradigm. Industrial platforms are being developed for the implantation of the new manufacturing ecosystem. With these advances in manufacturing, the benefits of the Fourth Industrial Revolution are being materialized and demonstrated.

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