Information Systems Frontiers
https://doi.org/10.1007/s10796-021-10213-w

Emerging Enabling Technologies for Industry 4.0 and Beyond

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Accepted: 28 September 2021

Abstract

Rapid advances in technology have spurred tremendous progress in developing the next generation of Industry 4.0 that was initially introduced in 2011 as a German strategic initiative for revolutionizing the manufacturing sector. Ten years have passed since 2011. In these ten years, numerous new and promising technologies and applications have been developed. The original concept of Industry 4.0, including the conceptual framework, technology framework, and enabling technologies, has experienced tremendous changes. As such, the new generation of Industry 4.0 emerges, which is also called Industry 5.0. Today, we are on the cusp of the Industry 4.0 evolution supported by a new set of enabling technologies. In such evolution of Industry 4.0, future Industry 4.0 requires a combination of recently emerging new technologies, which is giving rise to the emergence of the next generation of Industry 4.0 or Industry 5.0. Such technologies originate from different disciplines, including Artificial Intelligence (AI), 5G/6G, Quantum Computing, and others. The technologies in the original Industry 4.0 framework, such as Cyber-Physical Systems, IoT, etc., will be affected by Artificial Intelligence (AI), 5G/6G, and Quantum Computing. At this present moment, the emergence of a new era of Industry 4.0 can be seen. In this paper, we briefly survey the main emerging enabling technologies in Industry 4.0 as it relates to industries.

Keywords Industry 4.0 · Artificial intelligence · 5G · 6G · Quantum computing · Emerging technology · Enabling technology

1 Introduction

The concept of Industrie 4.0 was initially introduced in 2011 and officially announced in 2013 as a strategic initiative to revolutionize the manufacturing sector. Industry 4.0 mainly includes enabling technologies such as cyber-physical systems (CPS), Internet of Things (IoT), cloud computing, and others that represent the trend of industrial automation technologies in the manufacturing industry.

In the past ten years, Industry 4.0 are becoming increasingly advanced. Meanwhile, over the past ten years since 2011, new and promising technologies and applications have been developed. Industries have experienced many changes over the past ten years; in particular, the key change is that Artificial Intelligence (AI), 5G/6G, Quantum Computing are emerging in these ten years. Such new technologies provide a promising technology framework for the new generation of Industry 4.0. The original concept of Industry 4.0, including the conceptual framework, technology framework, and enabling technologies, has experienced tremendous changes. As such, the new generation of Industry 4.0 that is also called Industry 5.0, emerges. According to Breque (2021), Industry 4.0 has been around for some time; as an extension of Industry 4.0, Industry 5.0 is on its way.

Industries are under constant pressure to integrate emerging new technology to stay competitive. The transition to the new generation of Industry 4.0 will depend on the successful adoption of new technologies. Today, we are on the cusp of the Industry 4.0 evolution supported by a new set

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Published online: 10 January 2022

of enabling technologies. In such evolution of Industry 4.0, future Industry 4.0 applications require a combination of recently emerging new technologies, which is giving rise to the emergence of the future generation of Industry 4.0 or Industry 5.0. Such technologies originate from different disciplines, including Artificial Intelligence (AI), 5G/6G, Quantum Computing, and others. The technologies in the original Industry 4.0 framework, such as CPS, IoT, etc., will be affected by Artificial Intelligence (AI), 5G/6G, Quantum Computing, and others.

In the recent technological development, the new generation of Industry 4.0 can be foreseen that will dramatically increase the overall level of industrialization, informatization, and manufacturing digitization to achieve greater efficiency, competency, and competitiveness. At this present moment, the emergence of a new era of Industry 4.0 can be seen. In this paper, we briefly survey the main emerging new technologies in Industry 4.0 as it relates to industries.

This paper is intended to provide readers with a new perspective on Industry 4.0. This paper aims to introduce the future developments that exist in the exciting field of Industry 4.0; however, this survey is by no means meant to be exhaustive. In Section 2, we briefly discuss the evolution from Industry 4.0. Section 3 describes major new enabling technologies in Industry 4.0, and Section 4 concludes this paper.

2 The Evolution from Industry 4.0

According to Ilchenko et al. (2019), currently, we are in an era belonging to the end of the Third Industrial Revolution that began in the second half of the last century. Its characteristics include the development of information and communication technology (ICT), automation, robotics, etc. Industry 4.0 represents a fully automated production. CPS creates virtual copies of physical objects, controls the physical processes, and makes decentralized decisions. They can be integrated into a single network, as industrial Integration (Xu, 2016; Xu et al., 2016), interact in real-time, and learn for self-tuning.

Industry 4.0 is represented by CPS, IoT, cloud computing, and other technologies through integrating technologies and seeking completely integrated solutions (Xu et al., 2018).

CPS is one of the core foundations of Industry 4.0 (Xu, 2020). CPS presents a higher level of integration and coordination between physical and computational elements. In CPS, physical and software components are deeply intertwined, each operating on different spatial and temporal scales and interacting with each other. With the introduction of CPS, machines can communicate with each other, and decentralized control systems will be able to optimize production.

IoT has been revolutionizing the existing manufacturing systems; thus, it is a key enabling technology in Industry 4.0. IoT can enable the creation of virtual networks to support the smart factory in Industry 4.0 (Xu et al., 2018).

Cloud manufacturing is a technology that can contribute significantly to the realization of Industry 4.0. In cloud manufacturing, the concept of a network of resources in a highly distributed way is considered.

The new generation of Industry 4.0 will comprise emerging technologies including AI, 5G/6G, Quantum Computing, and others. Industry 4.0 enabled by such emerging technologies can be expected to have broad applications in the near future. At present, one of the challenges we face is to pay attention to such emerging technologies as well as include them in the technology framework of Industry 4.0 to make Industry 4.0 successful.

3 Emerging Enabling Technologies

Various technologies have been used for implementing Industry 4.0. These technologies include CPS, IoT, cloud computing, industrial information integration, and other related technologies (Xu et al., 2018). This section introduces the selected emerging technologies that are particularly significant for Industry 4.0 in the next decade. However, the coverage of emerging enabling technologies in this section is by no means meant to be exhaustive.

3.1 Artificial Intelligence

Industry 4.0 incorporates the digital revolution into the physical world, providing an encouraging new direction for artificial intelligence (Spiller, 2003; Kim et al., 2018). The artificial intelligence field has encountered a turning point mainly due to the recent advancements in industrialization and informatization. Artificial intelligence is much more than a research field: it is a future technology with the potential to redefine many tasks in Industry 4.0. According to the AI Index Report 2019, since 2011, global investments in AI startups have increased at an approximate annual growth rate of over 48%, reached \$40.4 billion in 2018 (Stanford Institute for Human-Centered Artificial Intelligence, 2020).

Artificial intelligence was founded as an academic discipline in the 1950s. The field was founded on the assumption that human intelligence can be precisely described and human-like intelligence through artificial approaches is possible. Turing's paper "Computing Machinery and Intelligence" (Turing, 1950), and its subsequent Turing Test, established the fundamental goal and vision of artificial intelligence. AI is the endeavor to replicate human intelligence through machines. AI is concerned with building smart machines capable of performing tasks that typically require human intelligence. In recent years, AI technologies have experienced a resurgence in industrialization and informatization (Chen et al., 2021; Haenlein et al., 2019; Lu, 2019; Mazurek & Małagocka, 2019; Tung, 2019; Xu, 2021; Zhang & Lu, 2021); the advancements in machine learning and deep learning are generating significant impacts in many sectors of industries. AI technologies are becoming an important technical component of Industry 4.0, helping to perform many challenging tasks in industrial operations.

The problem domain of AI research include reasoning, knowledge representation (Qiu et al., 2003; Sun et al., 2003), planning, learning, natural language processing (Kang et al., 2020), etc. Approaches include machine learning (Chi-Hsien & Nagasawa, 2019; Huang et al., 2019a; Kullaya Swamy & Sarojamma, 2020; Lu et al., 2018; Pradhan & Chawla, 2020; Wanigasekara et al., 2021; Yuan et al., 2010), computational intelligence, and others. Many techniques are used in AI, including artificial neural networks (Duan et al., 2019; Li & Li, 1999; Li & Xu, 2000; Panigrahi et al., 2019; Shi et al., 1996, 1999; Wang et al., 2010; Zhou & Xu, 1999, 2001; Zhou et al., 2003), deep learning (part of a broader family of machine learning, based on artificial neural networks with representation learning, Zhang et al., 2019a), genetic algorithm (Chaudhry et al., 2000; Jiang et al., 2009; Jin et al., 2014; Kurade & Latpate, 2020; Li et al., 2011a, b, 2012; Wang et al., 2011), case-based reasoning (Xu, 1995, 1996), knowledge management (Law & Chung, 2020; Wang et al., 2006, 2009; Xu et al., 2006; Zhang et al., 2019c), intelligent information processing (Duan & Xu, 2012; Feng et al., 2001; Finogeev et al., 2019), intelligent systems (Chen & Xu, 2001; Feng et al., 2001; Huang et al., 2019b; Li et al., 2001; Malhotra & Rishi, 2019; Tan et al., 2008), knowledge-based system (Feng & Xu, 1996a, b, 1997, 1999a, b; Feng et al., 2003; Gao et al., 2001; Li et al., 2006; Li, 1999a, b; Xu et al., 2001, 2008; Yang et al., 2001), and others. AI has become more sophisticated in recent years. AI is an interdisciplinary field, mainly a wide-ranging branch of computer science, and related fields include mathematics, philosophy, linguistics, and many other fields.

3.1.1 AI and Industry 4.0

Lee et al. (2018) indicate that as AI emerges to become the frontier of world-changing technologies, there is an urgent need to study its impact on Industry 4.0. Chun et al. (2018) predicted that AI is one of the most important technologies for industry 4.0. Peres et al. (2020) provide a review on AI in Industry 4.0 and detail the steps for a successful transition into Industry 4.0 supported by AI. Amaba et al. (2020) indicate the importance of digital transformation in Industry 4.0 and AI, which has grown exponentially with significant impacts. Kumar et al. (2021) study applications of AI under the industry 4.0 concept. In this study, AI adoption in the manufacturing sector is discussed, the digital twin concept for enabling better reasoning of the various interfaces is introduced, and the relevant AI algorithms are described. Bécue et al. (2021) present the AI technologies in manufacturing systems related to Industry 4.0, including AI-based techniques for production monitoring, optimization, and control. In the study by Dudukalov et al. (2021), the importance of AI methods in the control and operation monitoring of dynamic measurements in automation systems in Industry 4.0 is discussed. Merayo et al. (2019) study how AI techniques can assist the manufacturing process in Industry 4.0 environment by choosing the material for the envisaged applications.

According to Ilchenko et al. (2019), AI and machine learning will put Industry 4.0 forward, with the prediction that much more fundamental changes in business processes and business models caused by the integration of AI and other new technology, eventually will lead to the fact that business and industry are changing the way of operation.

3.1.2 AI and Industry 4.0: Industrial Applications

In industrial sectors, AI techniques have been explored for the advanced manufacturing process in Industry 4.0. Airbus focuses on six technical areas which adopt AI technologies (Airbus, 2021a), including (1) Knowledge extraction: Extracting knowledge from unstructured documents; (2) Computer vision: Transforming images into objects and activities based on deep-learning; (3) Anomaly detection: Finding hidden patterns in data; (4) Conversational assistance: Designing natural language based interaction systems; (5) Decision-making: Optimizing solutions for complex problems; and (6) Autonomous flight: Enabling the next generation of aerial vehicles with new capabilities.

3.2 5G/6G

3.2.1 5G

5G is the Fifth-Generation Mobile Network It is a generation of cellular networks designed to enhance the efficiency of data transmission. 5G networks have begun to spread worldwide and are on their way to being deployed across the world. The 5G networks are becoming more readily available. The first 5G networks are introduced in 2019 (Ilchenko et al., 2019). In Japan, a full launch is planned for 2020. Switzerland was the first country in Europe to launch 5G mobile communications (Ilchenko et al., 2019). Italy became the third country in Europe where fifth-generation mobile communications were established (Ilchenko et al., 2019). In Italy, it is expected that 5G will be deployed in 100 Italian cities by 2021. In Germany, it is likely that 90% of the country's population will be covered by 5G by 2025. Facing challenges left by 4G, 5G networks and standards are in the developing process. China provided the largest 5G-covering in the world (Ilchenko et al., 2019). Its breakthrough technology will allow 50 times less latency and transmission speed up to 20 times faster than the 4G technology. 5G networks provide higher capacities, higher data rates, lower latency, massive device connectivity, lower cost, and better consistent service quality than 4G networks. Research efforts have been made on both 5G and 6G. 6G as the next generation of 5G is at the corner. The key enabling technologies in 5G have been developed to offer its unique design and infrastructure considering the predicted capabilities of 6G.

In the heterogeneous IoT, wireless technologies such as 2G/3G/4G/5G, Wi-Fi, and Bluetooth have been used to connect billions of devices connected by wireless communication technologies. The 2G networks are designed for voice, 3G for voice and data, and the 4G for broadband Internet services. 4G significantly enhanced the capabilities of cellular networks that can provide IoT devices usable Internet access. 5G enables IoT devices to interact with a smart environment through intelligent sensors, can significantly enlarge the scope and scale of IoT coverage by providing faster communication and capacity, and can connect billions of smart devices to create massive IoT in which smart devices are interacting with each other. The spread of 5G contributes to increased usage of various IoT applications, which require massive connectivity, ultra-low latency, and security.

5G IoT integrates many technologies and is creating a significant impact on applications of IoT. 5G enabled IoT includes several key enabling technologies from physical communication to IoT applications, including 5G-IoT architecture, 5G enabled wireless connectivity, 5G cloud computing, 5G devices-to-device communication, 5G-IoT applications, etc. IoT applications need to use a hybrid model to realize real-time communications. The power of the 5G network will be essential for connecting IoT devices of all kinds.

Current research efforts have been made on 5G include (Zhang et al., 2019d):

5G Network Architecture In 5G IoT applications, more and more devices are being connected. A network architecture Named Data Networking (NDN) has been developed to support high-density IoT applications, and has been proposed for future Internet architecture. Network Functions Virtualization (NFV) is in the development process. NFV is a network architecture concept that uses ICT virtualization technologies to virtualize entire classes of network node functions into building blocks that may connect or chain together to create communication services.

5G, IoT, Artificial Intelligence, Data Analytics Integration The integration of IoT and Artificial Intelligence (AI) can dramatically accelerate the process of digitalization. IoT integrating AI can substantially help to realize smart cities. Artificial Intelligence of Things (AIoT) has been proposed as AI adds value to IoT through machine learning, and IoT adds value to AI through connectivity and data exchange. The term Analytics of Things (AoT) has been proposed to refer to the analysis of the data from IoT. AI, AIoT, AoT can be integrated with IoT networks. The integration of these technologies will offer technological innovation opportunities that create further advancements in IoT as well as many industrial sectors.

IoT Context-Aware Adaptation As many as billions of devices are connected, it brings the unprecedented scale and heterogeneity of IoT. IoT is expected to be autonomous and automatically adapt to dynamic changes in context.

Edge Computing Although 5G and edge computing are two technologies that are essentially independent of each other, both will open the door to many technological possibilities when integrated. The definition of edge computing is a distributed computing paradigm that brings computation and data storage closer to the location where it is needed to improve response times and save bandwidth. The 5G network and edge computing share the same goal: minimizing latency. Edge computing does this by processing and storing data outside the core network. By processing the information closest to 5G antennas, the time and distance for data transmission are reduced, and the connection speed dramatically increases. After integrating with 5G, the power of edge computing can increase dramatically. For IoT, edge computing helps to process much more information and the processing speed can be much faster. With edge computing and 5G, wireless infrastructure will be able to support more devices. Research indicates that the successful deployment of the 5G network will not be possible without a global edge computing infrastructure.

Energy Harvesting 5G energy harvesting technology is an appealing solution for ultimately prolonging devices and networks' lifetimes. Considerable research efforts have been conducted using energy harvesting technology in 5G wireless networks (Mehrabi et al., 2019). The beneficial role of energy harvesting technology in 5G networks has been emphasized.

Security and Privacy Research Current research efforts on security solutions for 5G cellular networks include the formal analysis of standards, application and device security radio protocol stack, inter-networking protocols, network slicing, and other aspects. The 5G is complex. 5G security and privacy research require the collaboration of industries, regulatory bodies, and standardization organizations.

Private Cellular Networks 5G private cellular networks are considered in smart manufacturing (Ericsson, 2021). In digitalizing manufacturing operations, typical applications include autonomous mobile robots (AMR), augmented reality (AR), collaborative robots (Cobots), digital twins, and asset condition monitoring.

3.2.2 6G

Although it is believed that the 5G is the means to connect everything together, especially for IoT, 5G is not sufficient for IoT devices to exchange various types of data in real-time. Some fundamental issues that need to be addressed are higher system capacity, higher data rate, lower latency, higher security, and improved quality of service (QoS). 6G technologies are emerging, which are expected to support higher network capacity, lower latency, and faster transmission of data than 5G networks. 6G is currently under development for wireless communications technologies supporting cellular data networks (Kim, 2021; Lu & Ning, 2020). Following the five generations of mobile communication systems from 1G to 5G, 6G represents the newest mobile communication networks. In theory, 6G networks data rate transmission can be ten times.

higher than 5G has (Ilchenko et al., 2019). 6G is expected to "connect everything, provide full dimensional wireless coverage, and integrate all functions, including sensing, communication, computing, caching, control, positioning, radar, navigation, and imaging, to support full-vertical applications" (Zhang et al., 2019a). According to Ilchenko et al. (2019), if the task of 5G is to provide high-speed throughput and minimum delay, 6G's goal is to connect the whole world. 6G will exhibit more heterogeneity than 5G and support more applications far beyond 5G. It is envisioned that 6G will take unprecedented transformations that will make it dramatically distinguishing from 5G.

Wireless connection technology generations have been spaced about ten years apart. 3G appeared in the early 2000s, 4G in 2010, and 5G in 2020. 6G is expected to launch commercially by 2030. 6G standardization is expected around 2028 (Ilchenko et al., 2019). 6G can be characterized by seamless connection, ubiquitous wireless intelligence, context-aware smart services, and many other characteristics. In 6G, new technologies will be deployed, such as terahertz communications, very large-scale antennas, and light communications. 6G will be a complicated system that consists of the key enabling technologies such as terahertz communication technology, visible light communication technology, polar coded transmission technology, multidimensional resource-allocation technology, orbital angular momentum technology, full-duplex technology, AI signal processing technology, recognition-driven network technology, and many others. On November 6, 2020, China successfully launched an experimental test satellite with candidates for 6G technology into orbit. The satellite is intended to verify the terahertz (THz) communication technology in space. In 6G, unmanned aerial stations and high-throughput satellites will be explored as new communication nodes that do not require cell-based mobile networks. The integration of terrestrial, airborne, and satellite networks into wireless networks is proposed for 6G systems (Saad et al., 2020). In terms of IoT connectivity, 6G will help realize the IoT of Everything.

3.2.3 Applications of 6G

The feature of 6G includes intelligent connection, deep connection, holographic connection, and ubiquitous connection. These technologies will provide complete coverage of the entire globe. 6G's unique dense device access, higher security level, low latency, and seamless global coverage will help its operations in an area much more exhaustive than 5G.

Ubiquitous Computing 6G ubiquitous computing capacity will help to realize the IoT of Everything.

Applications of AI Machine Learning in 6G IoT AI will help the 6G complex ecosystem, encompassing identification, authentication, sensing, communication, caching, computation, and localization services.

Integrating AI and Blockchain It is envisioned that to fully realize the potential of AI, blockchain, and 6G meeting the future intelligent, distributed, and security requirements in 6G, integrating these three technologies are expected (Jiang et al., 2021).

Integrating Blockchain and IoT The combination of blockchain and IoT can bring the following merits: decentralized network management, interoperability across IoT devices, IoT systems, industrial sectors; and traceability and reliability of IoT data. In 6G, a trend from centralization to distribution is arising. Blockchain is considered a promising technology for 6G to provide a distributed network management platform for resource and data sharing. Blockchain is deemed to be necessary to IoT in 6G (Guo et al., 2021; Jiang et al., 2021).

Network-in-a-Box (NIB) Industry 4.0 would require NIB to get positioned anywhere and provision seamless Internet connectivity. Ray et al. (2021) discuss 6G-NIB on top of vital aspects, such as key requirements, technological aspects, use cases, deployment schemes, variants, and open research issues and future directions. The applications related to industry 4.0 might benefit from 6G-NIB when proper connectivity features are sought.

3.2.4 6G Research Agenda

6G is an Active Research Area Current 6G research is focusing on cellular networks providing a good capability of heterogeneous radio access technology (RAT), terahertz (THz) communications, Visible Light Communications (VLC), Optical Wireless Communications (OWC), Dynamic Spectrum Management (DSM). The related research topics include artificial intelligence, digital twin, blockchain, intelligent edge computing, communications-computing-control convergence (Jiang et al., 2021). Other popular topics include wireless optical technology, free-space optical network, three-dimensional networking, quantum communications, unmanned aerial vehicles, cell-free communications, integration of wireless information and energy transfer, integrated sensing and communication, integrated access-backhaul networks, dynamic network slicing, backscatter communication, intelligent reflecting surface, big data analytics, holographic-type communications, pervasive intelligence, and ubiquitous global connectivity that can assist the 6G development (Chowdhury et al., 2020).

3.2.5 Implication to Industry 4.0 Future Development

Currently, We Are in the First Ten Years of Industry 4.0 As new technologies gain traction, networks become increasingly complex (Slalmi et al., 2021). In 2019, Ilchenko et al. predicted 5G and 6G's penetration into Industry 4.0. The era of Industry 4.0 and 6G will be here soon. With it will come a new range of possibilities for manufacturing and other industries as 6G enables better connectivity for digitalization, industrialization, and informatization.

Industry 4.0 Uses Industrial IoT (IIoT) Applications Various manufacturing industries have applied IoT and IIoT to advance production, distribution, transportation, service, and maintenance in the manufacturing process. IoT is becoming one of the cornerstones of Industry 4.0. In Industry 4.0, a strong interest is showing in deploying more IoT devices to develop Industry 4.0. Due to the rapid advances in technology and the emergence of 5G and 6G, IoT is expected to have significant technological innovation. In other words, the future trends of industrial IoT are impacted by 5G and 6G and their potential application. Along with the widespread adoption of 5G and the emergence of 6G, the conceptual framework, technology framework, and enabling technologies of future Industry 4.0 will face significant challenges, and Industry 4.0 is expected to evolve.

3.3 Quantum Computing

There is a growing trend towards applying quantum mechanics, a science describing the behavior of microscopic particles such as photons and electrons in computing, communication, and sensing. Quantum computing is an interdisciplinary field that seeks to understand the processing and transmission of information using quantum mechanics principles. Quantum computing is the exploitation of properties of quantum states such as superposition and entanglement to perform computation. The devices that perform quantum computations are called quantum computers. Quantum technologies are expected to create a massive paradigm shift in the way Industry 4.0 operates. Industry 4.0 has incorporated the digital revolution into the physical world; meanwhile, providing new directions for fields such as artificial intelligence, quantum computing, and nanotechnology (Kim et al., 2018). One of the drivers of the Industry 4.0 could be quantum computing, which harnesses quantum mechanical concepts such as superposition and entanglement to perform computation (Senekane et al., 2020), although a full-scale quantum computer has not yet been developed.

The bit is the basic unit of information in computing and digital communications. The bit represents a logical state with one of two possible values. These values are represented as either "1" or "0". Conventional computing technologies adopt bits of 0 and 1, and the computation is done with bits. Quantum computing is a new paradigm that uses quantum theory to replace current computing, the exploitation of collective properties of quantum states to perform computation. Quantum computing can process more data than digital data consisting of 0 and 1.

In quantum computing, a qubit or quantum bit is the basic unit of quantum information, the quantum version of the classic binary bit physically realized with a two-state device. Quantum mechanics allows the qubit to be in a coherent superposition of both states simultaneously, a property that is fundamental to quantum mechanics and quantum computing. Quantum computers use quantum superposition to process information in parallel, which provides a fundamental computing advantage over conventional computers.

As described above, the power of quantum computing is based on the quantum mechanics such as quantum superposition and entanglement (Gyongyosi & Imre, 2019). In terms of computing performance, these characteristics make it impossible to compare quantum computing with conventional computing. If quantum technology is applied to computing, it will enable rapid computational processing; as a result, it can overcome the limitations of existing digital computers, including supercomputing.

Currently, quantum computing is an important area of research, as evidenced by the market's rapid growth. The global quantum technology market is expected to reach approximately $65 billion by 2030 from $570 million in 2019, with an annual growth rate of 50.6%. The quantum information market will likely grow further as it can replace the traditional computing market (Kim et al., 2021).

3.3.1 Quantum Computation Technology

Here we review the most recent research on quantum computation technology in three main aspects: quantum communication, quantum sensing, quantum computing.

Quantum communication: Quantum communication is a field of applied quantum physics closely related to quantum information processing. It supports communication by constructing more secure networks than the existing networks by utilizing quantum states. Unlike conventional encryption, quantum communication is considered unhackable. The current aim is to build a quantum communication network infrastructure. The core of quantum communication is Quantum Key Distribution (QKD). "Today's cryptographic algorithms such as the widely used encryption via asymmetric keys will not be able to sustain attacks by the quantum computers of tomorrow" (Airbus, 2021b). Airbus aims to develop a future secure communications infrastructure for its aerospace platforms based on security-enhancing quantum information technologies, including algorithms, authentications, and keys.

Quantum sensing: Quantum sensing utilizes properties of quantum mechanics, such as quantum entanglement, quantum interference, and quantum state squeezing. Technology for new ultra-precision quantum sensors improves the precision of existing sensors/imaging. "Quantum sensors are effective at measuring physical quantities such as frequency, acceleration, rotation rates, electric and magnetic fields, and temperature with the highest relative and absolute accuracy" (Airbus, 2021b). It is believed that this could have direct applications in improving the navigation systems in which precise acceleration measurement is used to achieve position data. In addition, quantum sensors could act as payloads for a range of different applications, such as climate dynamics from satellites or underground resources surveying from an aircraft (Airbus, 2021b).

Quantum computing: It aims at overcoming the information processing limitations of conventional digital computers to improve computing performance. Quantum computing can dramatically reduce the time spent in computation time, even today's supercomputers. "The aerospace industry has complex computational needs in the areas of fluid dynamics, finite-element simulations, aerodynamics, flight mechanics, and more. Airbus actively uses advanced computing solutions in these areas" (Airbus, 2021b). It is believed that quantum computing, in tandem with more traditional high-performance computing (HPC) solutions, can help to solve key computationally intensive tasks.

3.3.2 State-Led Effort on Quantum Research

US: The National Quantum Initiative Act is an Act of Congress passed on December 13, 2018, and signed into law on December 21, 2018. The law gives the United States a plan for advancing quantum technology, particularly quantum computing (US Congress, 2018).

China: China is believed to be one of the leading nations in quantum information technology. Quantum information research in China dated back to 1998 when the National Natural Science Foundation of China (NSFC) convened the Xiangshan Science Forum for quantum information in Beijing. Soon after, several universities and research institutes, including the University of Science and Technology of China (USTC), the Institute of Physics of the Chinese Academy of Science (CAS), initiated experimental research in the field of quantum research. Currently, China has the world's largest quantum research facility-the National Laboratory for Quantum Information Sciences to help scientists build better quantum machines (Zhang et al., 2019b).

Russia: The establishment of a new national project called the National Quantum Laboratory (NQL) has been announced. Russia's state nuclear corporation Rosatom launched the National Quantum Laboratory to develop a quantum computer by the end of 2024. The lab aims to develop a 30–100 qubit quantum computer by the end of 2024 and potentially a universal computing machine with several hundred qubits. Rosatom is No. 1 in the world in terms of the number of simultaneously implemented nuclear reactor construction projects, three units in Russia, and 35 units at various implementation stages abroad (Rosatom, 2021).

EU: Europe published the Quantum European Project in 2006 and issued a quantum information communication statement, setting mid-to-long-term R&D targets for various quantum technologies. This document summarizes current issues in creating industrial quantum technologies and discusses concerns to be addressed by a roadmap for turning Europe's global leadership in research into a future world-class European Quantum Industry (EU, 2006).

UK: The UK National Quantum Technology Programme has induced a step-change in the nation's capabilities for establishing a new sector in future quantum information technologies (Knight & Walmsley, 2019).

Japan: Japan started developing quantum technology at the National Institute of Information and Communications Technology (NICT). The NICT has a long research and development history in quantum communication technologies and has made significant contributions to quantum technology in Japan, including quantum cryptography. Japan has established a roadmap for developing technology by 2040 (Masahiro, 2021).

Canada: Canada announced a significant investment to launch a National Quantum Strategy, committing $360 million over seven years. Reported on April 19 as part of the 2021 federal budget, this commitment will support research into quantum science and technologies and bolster an emerging quantum industry (Quantum Matter Institute, 2021).

3.3.3 Industrial R&D

Major IT companies are developing quantum information technology through their own R&D. Airbus aims to become an early adopter of quantum technologies to enhance aircraft performance and solve the most complex aerospace challenges (Airbus, 2021b). Building upon the first-generation Horse Ridge controller introduced in 2019, Horse Ridge II, a highly integrated system-on-chip (SoC) for quantum computers, was developed by Intel, offering enhanced capabilities and higher levels of integration for elegant control of the quantum system (Intel, 2021).

3.3.4 Research Focus

Quantum communication: The field of quantum communication is focused on the cryptographic base. The quantum communication industry will become a new infrastructure replacing traditional networks. Research on network equipment supporting quantum communication is on the agenda (Kim et al., 2021).

Quantum sensing: Quantum sensing is expected to have an overall impact on the industry as an initiative to measure objects that have not been measured in the past (Kim et al., 2021).

Quantum computing: Efforts have been made on researching and developing quantum computing as it can overcome the computational processing speed limit of the existing computing. It is expected to replace digital computers in the future. The challenge in quantum computing includes research on quantum algorithms that will replace the existing algorithms. Existing algorithms are configured based on bits, making them difficult to use in quantum computing, which is processed by qubit (Kim et al., 2021).

3.3.5 Implication to Industry 4.0 Future Development

Quantum information technology is a revolution that will bring about a new paradigm in ICT. In 2020, Senekane et al. predicted that one of the drivers of Industry 4.0 is quantum computing which harnesses quantum concepts such as entanglement, superposition, and tunneling to perform computation. Although a full-scale quantum computer has not yet been realized yet, however, Noisy Intermediate-Scale Quantum (NISQ) computers are already in use. Senekane et al. (2020) explore NISQ as a disruptive technology of Industry 4.0. Quantum computing is one of the most influential technologies in the near future. Currently, quantum information technology is state-led research and emerging industry, and it has great potentials for growth. Villalba-Diez and Zheng (2020) used quantum computing principles to present the strategic design of organizations from a novel point of view: Quantum Strategic Organizational Design (QSOD).

4 Summary

Despite advancements in Industry 4.0 in the past ten years since 2011 (Li, 2018, 2020), significant new challenges remain. Research has predicted that Industry 4.0 will continue to embrace cutting-edge technology. Presently, it is clear that the new evolution has been emerging from the currently ongoing process of Industry 4.0 proposed ten years ago. AI, 6G, and Quantum Computing represent a paradigm shift from existing technologies, as revolutionary new applications become available. AI, 5G/6G, Quantum Computing are rising technology that will drive innovations and contribute significantly to the future development of Industry 4.0 that enables moving industries to a higher level. The new technology is capable of integrating both new and classical Industrial 4.0. AI, 6G, and Quantum Computing will have a transformative impact on future industries and technologies. Organizations will face the complex realities of implementation ranging from introducing new AI, 6G, and Quantum Computing technologies and applications to adapting or replacing core technologies developed in the earlier generation of Industry 4.0. Because of the emerging new technology, we can foresee a new convergence or integration of technologies. New and exciting challenges can be foreseen for both foundational and industrial research, and new opportunities for industrialization and informatization can also be foreseen. Due to the arrival of AI, 6G, and Quantum Computing technologies, there is the need to embrace new technologies that will help industrial organizations with the adaptation of existing enterprise architecture, ICT infrastructures, processes, and others to support the transformation. AI, 6G, and Quantum Computing are expected to introduce promising technologies for developing a new generation of Industry 4.0. We can predict that the integration and co-evolution of AI, 6G, Quantum Computing, and Industry 4.0 are on the horizon. By delivering informatization through AI, 6G, Quantum Computing technology, we are laying a foundation that can help to drive innovation in industries and boost the economy.

This paper reviews the recent research on Industry 4.0 from the perspective of emerging new technologies. We first introduce the challenges Industry 4.0 faces and then discuss the emerging technologies that might be used in Industry 4.0. Next, we present some emerging technologies, including AI, 6G, Quantum Computing. Afterward, we analyzed the research challenges and future trends associated with Industry 4.0. Unlike other Industry 4.0 papers, the main contribution of this paper is that it reviews emerging technologies for Industry 4.0 and beyond.

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