Potential applications of 5G communication technologies in collaborative intelligent manufacturing

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Abstract: Nowadays most of the communication technologies used in the manufacturing industry are still wired, including various fieldbuses and dedicated industrial Ethernet technologies, though wireless communication technologies including WiFi and ZigBee are recently being adopted. This study is to investigate the integration of 5G wireless communication technologies with collaborative intelligent manufacturing (CIM) processes and systems. 5G technologies and typical scenarios including enhanced mobile broadband, massive machine type communications, and ultra-reliable low latency communication are introduced. Various possible applications or business slices of 5G in CIM are analysed, including human–machine interfaces and production IT, process automation, factory automation, logistics and warehousing, monitoring, and maintenance. These applications are analysed by the functions as modules with the extended 5C architecture. A modular collaborative production approach is suggested to combine modules to achieve on-demand resource allocation and complete flexible tasks in CIM systems. Related research challenges and opportunities are also discussed.

1 Introduction

In response to the increasing requirements of the manufacturing industry, many countries and institutions have proposed new concepts for future factories. Industrie 4.0, an idea first appeared in Germany in 2011, describes the fourth industrial flexibility of production lines, and the efficiency of factories [1], whose reference architecture [2] is shown in Fig. 1. In the following year, General Electric in the USA proposed the Industrial Internet, which is an open, global network that connects people, data, and machines. The goal of the Industrial Internet is to upgrade key industrial areas (as shown in Fig. 2 [3]). In 2015, Japan put forward the Japan Industry 4.1J, extending industrial intelligence from a single factory to the overall value chain of the industry. Besides, China highlights that informatisation and industrialisation need to be deeply integrated, which is one of the critical directions in the Made-in-China 2025 strategy. Since more and more organisations are joining the study of collaborative intelligent manufacturing (CIM), how to make the current factories smart is an active research topic.

We collect the core components form Industrie 4.0 or Industrial Internet, Japan Industry 4.1J and Made-in-China 2025 strategy, which can be described as the application of cyber-physical system (CPS) [4]. In this field, Lee et al. [5] proposed a five-level architecture, namely the 5C architecture, to guide the implementation of CPS. Then Xu et al. [6] pointed out that the 5C architecture is a generally adopted architecture of the Industrial Internet. Fig. 3 shows that the extended 5C architecture consists of five levels, including smart connection level, data-to-information conversion level, cyber level, cognition level, and configuration level [5]. We then added the objects and corresponding challenges at each level.

In the 5C architecture, initially, the large amount of sensor data collected from the smart connection level is converted into the component- or machine-related information through the conversion level and then passed up to the cyber level, where a series of computers perform cloud-based computing. Then the fusion information passes to the cognitive level, where workers interact with machines. Finally, the highest level, namely the configuration level, is obliged to make intelligent decisions and perform self-adaptive operations according to specific conditions.
Since the multiple levels of the 5C architecture are involved from data to decisions by information and computing, many communication challenges for each level in this extended architecture are addressed in the CIM as follows:

(i) Large-scale devices are connected in the smart connection level. Obtaining accurate and reliable data from machines and their components is the first step in implementing the industrial Internet. The idea of the IoT will be realised in the future, so the number of underlying devices will be much more enormous. Therefore, the primary consideration is about how to access these terminals and maintain their high reliability. Meanwhile, reducing the power consumption can not only enhance the durability of the sensors but also decrease the deployment time. Artificial intelligence (AI) can be combined with 5G technology and applied to this level. Due to the increasing number of devices, the factories are dealing with the massive disordered data, where the ones with high reliability can be remained and used to achieve real-time manufacturing.

(ii) In the data-to-information conversion level, the collected data from the smart connection-level need to be converted into useful information, especially for equipment health condition monitoring. Currently, the real-time performance of the data is not well guaranteed, so it is a novel direction to find the data analysis method through edge computing, to realise the fast interaction between the control centre and the terminals. Another measure is to apply direct communication between devices, which will reduce the whole amount of data transmitted because the closed-loop transmission from the underlying level to the upper level and then in reverse is not needed.

(iii) The cyber level collects the information from the data-to-information conversion level and can be regarded as the fusion centre in this architecture. Machines in the factory can form an integrated network, and they can compare not only with each other but also with their previous status. Therefore, multiple devices working collaboratively can be implemented smoothly. One research direction is to accelerate the analysis and calculation process, which requires ultra-low latency.

(iv) In the cognition level, workers and experts are involved. They make manufacturing decisions according to the previous information analysed from the cyber level. During this period, the visualisation and customisation would increase the readability and practicability. At present, wearable devices and other technologies related to virtual reality and digital twins have emerged in factories. However, future intelligent factories still need to conduct an in-depth exploration of visual information and have higher requirements for parameters such as user transmission rate.

(v) The configuration level makes it possible for devices to achieve self-configuration and is over the cognition level in the CIM. For example, intelligent and accurate controls depend on feedback from individual steps of the device itself; predictive maintenance will be carried out by sensing its health status; meanwhile, the devices should respond to emergencies and implement adaptive functions. These functions are highly demanding on network performances, especially latency and communication reliability.

Future CIM systems will ultimately realise self-examination capabilities, including self-aware, self-predict, self-compare, and self-configure. In the face of the challenges, there are several requirements to overcome, including large connection density, low power consumption, high reliability, ultra-low latency, high transmission rate. We suggest that the continually evolving 5G communication technologies can be employed to address these challenges in the manufacturing industry.

In our literature review, we focus on studies on 5G technologies and potential applications in CIM, rather than networking technologies and optimisation algorithms for 5G networks, which are referred to other previous publications. For example, Hatzivasilis et al. [7] proposed a hybrid protocol and framework for industrial networks; Mannweiler et al. [8] presented an intelligent cross-domain 5G network management system and related optimisation functions; Mahmood et al. [9] provided the enhancements to meet the constraints of 5G ultra-reliable low latency communication (uRLLC) applications. We do not consider studies on pure 5G technologies either. Moreover, application areas other than manufacturing are not considered, e.g. smart city [10], intelligent transportation [11], and smart grids [12]. Therefore, we limited our survey to studies on 5G applications in the manufacturing industry and searched related databases, where the major journals in communication, electronic information, mechanical engineering, and so on are covered. Besides, we also referred to official white papers and intended to propose our opinions based on them.

The rest of this paper is organised as follows. Section 2 introduces the 5G framework, including typical scenarios and critical technologies. Section 3 highlights potential applications of 5G in CIM. Section 4 defines modular collaborative production and its effects on flexible manufacturing. Section 5 discusses the challenges and opportunities of integrating 5G technologies in CIM. Section 6 provides some concluding remarks.

2 5G technology framework

The future of 5G communication network will be developed in the direction of better performance, smarter deployment, and more

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**Fig. 3** Extended 5C architecture

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2 5G technology framework

The future of 5G communication network will be developed in the direction of better performance, smarter deployment, and more
flexible functions. Many institutions researched 5G and developed a 5G vision [13]. As early as 2013, several countries have established official 5G organisations, including China's IMT-2020 (5G) promotion group, South Korea's 5G Forum, Europe's 5GIA, Japan's 5GMF, the US's 5G Americas, Brazil's 5G Brazil, and so on. To establish a globally unified 5G standard and better promote the development of 5G industry, these 5G official organisations are gradually strengthening their international cooperation, organising global 5G summits, and exploring series of topics such as policy strategies, spectrum planning, standards development, and vertical industry applications. With the ongoing investment and active promotion from government, industry, and academia, 5G technologies have been evolving rapidly.

### 2.1 Three typical scenarios

According to the classification of the International Telecommunication Union, the current 5G scheme can be categorised into three typical scenarios: enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and uRLLC.

Human-centric communication performance indicators, such as user experience rate, are the primary goal of the eMBB scenario. Use cases for mMTC include monitoring and massive wireless sensor networks. The essential goals of the mMTC scenario include high connection density, low battery life, and low cost. Besides, there are many typical use cases related to uRLLC, such as remotely controlled machines and intelligent transportation systems. There are two critical requirements of the uRLLC scenario, namely low latency and high reliability. Table 1 shows three scenarios of 5G and their corresponding requirements. Some major factory-related cases are categorised into three groups according to their characteristics. The core indicators, which are the expected values in the immediate future, come from 3GPP-released criteria [14] and become the targets of the relevant industries. It is shown that these indicators may be suitable for different scenarios, and play particular roles in specific conditions. Note that only the most relevant indicators of the use cases are displayed, while the other ones, which are not important enough in particular scenarios, are filled with 'N/A' in the table. For instance, the augmented reality case belongs to the eMBB scenario, therefore its main requirements focus on the reliability and latency properties. Meanwhile, the peak data rate and mobility are constrained by 3GPP criterion [14], as for the other indicators, are not shown in our table.

#### 2.1.1 Enhanced mobile broadband

Mobile broadband emphasises human-centric applications. Based on the existing technology, the eMBB scenario will broaden new areas and further increase the seamless user experience. This application scenario, according to Table 1, mainly includes augmented reality, virtual reality, remote access and control. The eMBB scenarios have significantly higher requirements for data rate and user experience rate, allowing for appropriate relaxation of time latency and reliability, as well as a small degree of mobility.

#### 2.1.2 Massive machine type communications

Typical applications of mMTC include a series of large-scale device connection, monitoring, and preventive maintenance services. The terminal equipment is generally extensive in quantity and big in size. As a consequence, there is a high demand for connection density, as well as industry diversity and variability. However, most of the terminals are stationary. Except for security monitoring, the requirements for latency and mobility are relatively lower. The terminals also require an extremely long battery life to save the replacement costs.

#### 2.1.3 Ultra-reliable low latency communication

The uRLLC scenario has strict requirements on the capabilities of latency and reliability. Typical applications cover control of machines through wireless systems, industrial automation, mobile robotics, logistics, and so on. Industrial control and robotics applications require the accurate end-to-end transmission of control signalling. Deterministic latency is the basis for the cooperation between multiple control systems. Even in extreme scenarios such as autonomous driving, the latency needs to reach <1 ms. The ultralow latency requirement is to optimise the absolute value of the latency, from tens of milliseconds to several milliseconds, which has become one of the important features for the future communication networks.

### 2.2 Progress of 5G key technologies

Since the concept of 5G was defined, many organisations have studied standard rules and technologies. Meanwhile, researchers have been continuously exploring the key techniques of 5G, and some have already made significant progress.

#### 2.2.1 Network slicing

Network slicing is an implementation of on-demand networking. It is difficult for 5G to satisfy the above three scenarios with totally different communication requirements by setting up one network. An example of a multi-5G slice coexisting on the same infrastructure is shown in Fig. 4 [15]. This framework can implement not only 5G slices for typical smartphones but also play critical roles to support autonomous driving slicing.

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**Table 1** Three scenarios of 5G and their transmission requirements

| 5G scenarios | Related cases | Peak data rate | User experience rate | 5G transmission requirements [14] |
|--------------|--------------|----------------|----------------------|---------------------------------|
| eMBB         | augmented reality | >1 Gbit/s | N/A | Connectivity density |
|              | virtual reality | >5 Gbit/s | 1 Gbit/s | N/A |
|              | remote access and control | >1 Gbit/s | > 5 Mbit/s | N/A |
| mMTC         | massive wireless sensor networks | N/A | N/A | Power consumption |
| uRLLC        | automation control | N/A | N/A | Reliability |
|              | based on security | N/A | N/A | Latency |
|              | predictive maintenance | N/A | N/A | Mobility |
|              | motion control | 1 Mbit/s | N/A | 20–100/ device |
|              | machine-to-machine control | N/A | N/A | 5–25 years’ service life |
|              | mobile robot | >10 Mbit/s | N/A | 10 km/h |
|              | logistic | N/A | N/A | N/A |

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Similarly, massive IoT scenarios can be sliced with a strict requirement of connectivity density. 5G should ensure that the end-to-end system operates under controlled and secure conditions at any supported slice. One of the current research directions is to study its application in 5G mobile communication systems. Ni et al. [16] demonstrated that network slicing had become a promising solution in service-oriented 5G architecture.

Fig. 4 illustrates that network slicing can deploy functions and orchestrate architectures flexibly. Therefore, differentiated services for various businesses are also feasible. For instance, Yoo [17] proposed a top-down approach and NextGen RRC architecture. Challa et al. [18] presented SuperFlex, a multi-domain 5G wireless network architecture based on network slicing. Wang et al. [19] proposed a mobility driven network slicing to enable mobility management in 5G networks.

2.2.2 Network function virtualisation (NFV): NFV is a prerequisite for realising the network slicing. In essence, NFV is to transfer the software and hardware functions of the dedicated devices to virtual machines (VMs). Based on the industrial standard, these VMs are commercial servers with low cost and simple installation characteristics. To improve the performances of NFV, many experts and scholars studied them from network architecture perspectives. Shen et al. [20] proposed vConductor to solve NFV management; and Lee and Lee [21] provided a fault localisation method when the NFV framework does not work. Moreover, Naik et al. [22] developed a performance monitoring and bottleneck detection tool for NFV.

After the concept of NFV was proposed, many applications have been studied to solve multi-propagation problems, verification and authorisation issues, and so on. Shih et al. [23] introduced S-NFV, which is a security scheme for NFV applications. Xu et al. [24] studied NFV-enabled multicasting to maximise network throughput. Guija and Siddiqui [25] used the NFV-based SONATA Service Platform for authentication and authorisation mechanisms.

2.2.3 Software-defined network (SDN): SDN defines the concept that software is obliged to control the network and fully extend the network capacity. The SDN architecture has two main features: (i) the separation of the control surface and data surface, and (ii) the concentration of the control surface. By introducing SDN, the closed architecture of traditional telecom network can be transformed into a flexible and service-oriented one. Many researchers had integrated SDN with other technologies. Alcom et al. [26] built an SDN testbed which can support many configurations for pseudo-real-world SDN experiments. Tuyaba et al. [27] studied generalised IoT-SDN solutions and provided a critical view of the IoT and SDN technologies. Albert et al. [28] showed actor-based modelling to seamlessly model SDN applications.

There are also new challenges for SDN, mainly about reconfiguring network functions, designing interface protocols, and optimising the architecture. For instance, Gheorghe et al. [29] developed a tool to help network administrators to find faulty network links. Chandrasekaran et al. [30] presented a prototype implementation that can recover failed SDN-Apps. Tatang et al. [31] built an SDN-GUARD system for detecting and mitigating SDN rootkits. Zhou et al. [32] proposed a method to identify SDN devices reliably.

2.2.4 Mobile edge computing (MEC): MEC provides cloud computing capacity close to mobile users. It pushes content distribution to the user side (such as a base station) so that services are deployed in a distributed condition, thus better supporting the 5G requirements with medium or low latency, and high bandwidth. Wang et al. [33] applied the MEC on a 5G scenario and studied the edge server placement problem in MEC environments.

To accelerate the development of MEC technology, researchers have overcome various technical challenges such as network integration, security, performance, and fault tolerance. Hu et al. [34] studied a MEC system utilising cooperation to overcome the doubly near-far effect for the farther mobile device. Wang et al. [35] established a mobile edge network (MEN) and scheduled tasks in MEN to reduce end-to-end delay for MEC tasks. Zhang et al. [36] studied an online dynamic tasks assignment to balance energy consumption and delay for a MEC system with energy harvesting capability.

2.2.5 Cloud radio access network: At present, the LTE access network adopts a flat network architecture. In the future, 5G may adopt the cloud radio access network architecture, i.e. Cloud-RAN (C-RAN). Generally, the C-RAN includes a group of base band unit placed in a cloud-based data centre and a large number of low-cost remote radio heads deployed in a cell [37]. In C-RAN, the baseband signal processing and wireless functions are decoupled. Ranaweera et al. [38] analysed the applicability of ‘Fronthaul technologies’ for the C-RAN architecture and believed that future-proof fronthaul network can be modelled for 5G C-RAN.

C-RAN transmits wireless signals between centralised nodes and a radio access network, which is based on the architecture with centralised processing, cooperative radio, and real-time cloud computing functions. C-RAN, in this way, can construct service areas that cover hundreds of cells so that they can be combined to adopt cooperative technology, which can reduce interference and power consumption, let alone improve spectrum efficiency.

Nowadays, the C-RAN research topics include the construction of test platforms, the combination with cloud computing, and the development and enhancement of network security. Luo et al. [39] renovated the infrastructure of C-RAN and built a cloud field LTE testbed environment. Liu et al. [40] proposed a multihop C-RAN network to access mobile clouds so that they can be combined to improve the communication and computation cooperation. Lisi et al. [41] proposed a methodology for C-RAN deployment from cost and energy-efficient aspects.

2.2.6 Device-to-device (D2D) technology: The D2D technology not only enables direct communication between terminals but also expands the network connection and access methods. At present, D2D communication can be either direct communication between devices or completed with the assistance of network devices. Most of the current D2D communication needs the assistance of network devices due to the capacity limitations of terminals [42]. Therefore, 5G technology comes into use to achieve this D2D function. D2D technology is to realise high-speed data transmission in the existing cellular communication network when the distance between terminals is relatively close, therefore the quality of the channel is better. At this time, D2D communication technology with multiplexing system frequency resources can achieve large throughput, and the interference in D2D communication to the original cellular communication of the system can be well controlled by power control. D2D communication increases the endurance of mobile terminals and reduces the transmission power in close proximity. Meanwhile, data parameters are transmitted directly between devices without passing through the base stations. It can not only reduce the communication burden of the base stations and realise the high rate transmission at short distance but also increase the total throughput of the cell and improve the spectrum utilisation rate.

There are many applications of the D2D technology. Botsoy et al. [43] proposed a location-dependent resource allocation scheme.
for mobile D2D communications for automotive safety applications. Lien et al. [44] introduced D2D proximity services which support direct data exchanges between user equipment. Wang et al. [45] proposed an information-centric wireless network virtualisation architecture, where D2D enables the sharing of the infrastructure and content among different service providers. D2D communication technology plays an important role in achieving local machine-to-machine (M2M) communication, especially when it comes to the massive machines burden problems in the industrial area.

All in all, 5G will be developed into an advanced communication technology with lower latency, higher transmission rate, and better business experience, as well as the characteristics of ubiquitous perception, connectivity, and intelligence. The evolution of 5G can promote the deep integration of informatisation and all aspects of social life, especially the convergence of mobile informatisation and industrialisation. Since 5G will fully connect among people and things, it will become a fact to achieve ubiquitous deep collaboration and personalised customisation, as well as to form a new industrial ecosystem.

3 Potential applications of 5G in CIM

Currently, the vast majority of communication technologies used in the manufacturing industry is still wired, which includes communications for sensors, actuators, and controllers in interconnected automation systems. Due to the past static and legacy production facilities, the wireless connections were not popular. Meanwhile, most of the existing wireless technologies cannot meet the strict requirements of industrial applications, such as their slow transmission speed, poor real-time capability, high latency, and high security risk. For example, WiFi, ZigBee or other wireless communication technologies had problems with data packet loss and other issues, which severely affect the equipment safety, and even threaten the security of the production line.

As mentioned above, the current industry is facing several challenges, which may be solved by improving the performance of network communication, including high connection density, low power consumption, high reliability, ultra-low latency, and high transmission rate. These requirements appropriately correspond to the slices of 5G technologies as described above. Therefore, 5G can be a key enabling technology to support the CIM.

According to the white paper published by 3GPP [14], together with the relevant literature, this white paper created five critical business slices for smart factories, including HMIs and production IT, process automation, monitoring and maintenance, factory automation, logistics and warehousing, which will revolutionise the CIM. Table 2 shows the critical business slices and their 5G requirements corresponding to eMBB, mMTC, and uRLLC scenarios (slices). There are also some detailed modules in each critical business slice, which will be described in this section. A module is usually described as a set of functionally or structurally independent components [46]. According to Salihieh and Kamrani [47], the overall functions performed by a product can be divided into sub-functions, which can be implemented by different modules. The modularisation of manufacturing has a strong relationship with the modularisation of processes and resources, which has a positive impact on cost, quality, flexibility, and cycle time [48, 49].

In the subsections below, we will discuss suggested business slices in CIM.

3.1 HMIs and production IT

Human–machine interfaces (HMIs) mainly apply to the interaction between human and manufacturing equipment including machines and robots. Production IT encompasses IT-based applications, such as manufacturing execution systems and enterprise resource planning systems. HMIs and production IT can employ 5G technologies in two typical modules:

(i) Augment reality-based glasses can obtain visual images of robots inside, putting on gloves with feedback function and operating the robot arm to complete the assembly tasks. This application will employ 5G eMBB slice due to the high transmission rate requirement, which plays the main role in the HMIs and Production IT application areas.

(ii) Remote access and control, a 5G-based real-time synchronous operation, is not only suitable for small-volume customised production, but also high-risk environments such as pollution, radiation, and explosion. The latency and reliability characteristics enable remote and interactive human–machine control and realise the real-time synchronisation actions of the factory inside and outside, which is addressed by the 5G uRLLC slice.

As Fig. 5 shows, these two modules are involved in decision making from human aspects, aiming at improving the performance of 5C architecture, especially in the cognition level.

3.2 Process automation

Process automation factories include electricity, water, petroleum, and food processing, so there is a general need to monitor and automatically control various process parameters (flow, temperature, liquid level, pressure etc.) in the production process. Meanwhile, their health status also needs to be perceived to ensure a stable operation. In addition, we may have collaborative mobile robots to move freely for meeting the material needs and achieving flexible production. For these cases, 5G uRLLC slice will make them possible.

The production process requires connecting people, machines, objects, and systems with highly distributed facilities. These features are concerning the 5G mMTC slice. So, the efficiency can be improved, and the amount of workforce, material and energy consumption in scheduling, material delivery, and other industrial fields can be reduced by 5G technologies.
Process automation in the CIM has several modular applications and improvements corresponding to the 5C industrial architecture in Fig. 6. Firstly, logistics and massive wireless sensor networks for smart connection-level where AI technologies can be applied and the security of underlying devices should be paid attention. Secondly, machine-to-machine control and health status perception for the data-to-information level, where D2D technology can be used to alleviate the larger-scale data pressure. Thirdly, mobile robots (automatic guided vehicles, AGVs) for the cyber level and cloud computing technology can be combined with the CPS system and make it possible for adaptive planning and control [50]. It is necessary to develop these modules and increase the performances of the 5C industrial architecture in these three levels.

3.3 Factory automation

Factory automation covers massive wireless sensor networks at the smart connection level, machine-to-machine control at the data-to-information level, motion control and mobile robot at the cyber level, and automation control based on security at the configuration level. The potential technologies can be combined with the several first levels have already discussed, while the configuration level can be expanded to some key applications of manufacturing such as pay-as-you-go business models, flexibility in deploying and customising solutions [51]. Fig. 7 indicates that these modules are relevant to four levels of the 5C industrial architecture.

It is a driver of industrial mass production, which needs to communicate between all machines to perform common tasks, such as controlling and coordinating workpieces, switching them from one device to another. With the increasing size of data generated during the manufacturing process, the number of networking between machines is very likely to grow as well, which is the situation corresponding to the 5G mMTC slice. Meanwhile, this slice occupies a larger space in the factory automation area. For example, the wireless communication of many current terminals with various functions can pave the way for highly modular and flexible production modules that interact effectively with each other by using 5G slices.

The 5G uRLLC slice also plays a vital role in factory automation. For example, when the actual operation deviates from the predetermined specification, the cloud system will alert in real time and locate the failure position, so the problem can be solved immediately and accurately. Besides, attention should also be paid to potential vulnerabilities based on the security operation of automation control. Thus, these applications often have high requirements of communication latency and service reliability, which can be satisfied by the 5G uRLLC slice.

3.4 Logistic and warehousing

Logistic and warehousing refer to the organisation of the flow and storage of materials, semi-finished products, and final products. Mobile robots and mobile platforms (such as AGVs) are of great use in this area and can achieve automation processes such as distribution, transportation, and sorting with logistics resources. It significantly affects the manufacturing efficiency. In this case, 5G uRLLC slice plays the main role in the logistics and warehousing area by maximising their moving flexibility, as well as with perception to respond to their situations.

Also, 5G mMTC slice is helpful to logistics and warehousing systems, which can operate in indoor and outdoor. Indoor logistics is always operated in a factory for AGVs or forklifts. For outdoor logistics, the logistics are needed among different locations. Both indoor and outdoor logistics require large amounts of interactions with the public network. So, 5G mMTC slice plays a crucial role here.

Fig. 8 shows detailed modules which are relevant to the 5C architecture and can improve its properties from four levels: smart connection level, data-to-information level, cognition level, and configuration level.

3.5 Monitoring and maintenance

Monitoring and maintenance can be applied to massive wireless sensor networks at the smart connection level, health status perception at the data-to-information level, remote access and control at the cognition level, predictive maintenance and automation control based on security at the configuration level. Fig. 9 indicates that the 5C industrial architecture can be improved from these modules at four levels.

5G eMBB and uRLLC slices are also employed and corresponding to independent ranges of communication technologies. For the 5G eMBB case, monitoring here refers to the supervision of operations and machine states during manufacturing, without affecting the manufacturing process, which may include condition monitoring based on extensive sensor data. In industrial factories, manufacturers can gain insights into environments and adjust themselves timely by the 5G eMBB slice to maximise efficiency if control can be achieved in real time.

For the 5G uRLLC case, analysing the equipment health condition in real time on the edge level to implement predictive maintenance is an important requirement from the maintenance aspect. Once the system fails to execute, manufacture systems will locate and resolve related errors or failures as soon as possible. As a result, 5G uRLLC slice has to be included in the monitoring and maintenance area.

4 5G-based modular collaborative production

As described above, five critical business slices are proposed to meet the requirements for flexible configuration of 5G networks in CIM, especially for the allocation of resources on demand. While creating slices, resources in the infrastructure need to be scheduled. Due to the mutual independence of various resources, network slice management also carries out collaborative management among different resources. In the proposed smart factory architecture, a multi-level, modular management model is demonstrated to make the management and collaboration of the entire factory more generic, flexible, and scalable.

Figs. 5–9 show the modules of white and grey blocks in critical business slices. White blocks represent modules that appear only once among them, while grey blocks appear more than once. As it can be seen, the list of grey blocks includes remote access and control, automation control based on security, massive wireless sensor networks, real-time monitoring, M2M control, mobile robots, logistics, health status perception, and predictive maintenance. It is noted that, on rare occasions, only one module (white block) is used to complete the production task. Instead, several modules can be combined to achieve a collaboration goal. Therefore, we propose that modular collaborative production will be of great use in smart factories. Regarding modular production, Beitz and Pahl [52] refer it to products and components that realise various functions by combining different modules, so that manufacturing companies can customise products by assembling various modules. Baldwin and Clark [53] regard modular production as building complex products or processes from smaller subsystems that can be designed independently. Therefore, besides the on-demand resource allocation, modular production systems can also achieve high flexibility and versatility of smart factories.

In our created slices, the modules within the slices can be deployed flexibly according to requirements of critical business. Therefore, smart manufacturers will integrate several typical modules to perform specific tasks. With the introduction of connected industries or industrial Internet scenarios, the number of Internet connections and data exchanged between controls will increase significantly. In this aspect, wireless communications using 5G technologies can pave the way for highly modular and flexible production modules that interact efficiently and collaboratively.

5 Research challenges and opportunities

Few studies on the integration of 5G technologies into current factories were reported. Some challenges for these integrations and future trends are discussed as follows:
(i) Security issue must be considered and prioritised in 5G wireless technologies because privacy protection has raised many concerns in the CIM area. The security of each level in the smart factory depends on each other. The current protection strategy designed for each level is not robust enough for cooperation among different levels. A decentralised authentication and trust model in 5G framework may be employed for privacy protection between devices. Blockchain has become one of the most frequently discussed methods for securing data storage and transfer through decentralised, trustless, peer-to-peer systems [54], which should be considered in the future.

(ii) Implementation of 5G transmission requirements is still ongoing. Table 1 reveals that 5G technologies have high demands for data transmission rate, latency, communication reliability, connection density, and so on. In some extreme cases, the security needs to reach 100%. However, the performance requirements vary in different scenarios, so 5G will inevitably keep developing until satisfying the mission requirements. In addition, some advanced technologies, like AI and machine learning, can also be combined into the 5G-based CIM processes, which can improve the efficiency of manufacturing, especially at the smart connection level.

(iii) Modular collaborative production plays an important role in achieving an allocation of resources on demand. Besides, static sequential production will increasingly be replaced by unique modular production, which provides a high degree of flexibility and versatility. 5G technologies enable various manufacturing objectives in a collaborative and flexible way.

(iv) There are high demands to converge the heterogeneous networks. Many types of current systems co-exist to form information islands. Therefore, it is necessary to make interconnection and interoperability properties and then achieve CIM. A 5G network is helpful for seamless access performance and integrating multiple heterogeneous networks.

6 Conclusion

Currently, the 5G network is developing fiercely, and the key technologies of 5G are becoming more and more mature. The network slicing enables different communication standards to be satisfied. At the same time, the 5C architecture of the industrial Internet also clearly reveals the transmission process from data to information, then to decision making. The connection between people and facilities in factories has been partially realised. To fully achieve CIM, it becomes an inevitable trend to apply 5G technologies into factories. Therefore, this paper first introduces the 5C architecture for CIM and then summarises the state-of-the-art of 5G technologies. Moreover, aiming at the challenges of 5C industrial levels, this paper discusses how to apply 5G technologies to potential areas in CIM. Finally, the 5G-based modular collaborative production is suggested, so the on-demand resource allocation and flexible manufacturing can be achieved.

Through the review of 5G technologies, this paper tries to establish an efficient interconnection between production devices, smart products, logistics systems, and information management. We believe that the CIM systems will integrate the 5G technologies for heterogeneous network convergence, automated data collection, data analysis, and so on, and have a bright future.

7 References

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