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Key Technologies and Development Trends of Networked Integration of Measurement and Control Systems for Intelligent Manufacturing

Jiaxin Liu

Tianjin University, Tianjin, China
929836617@qq.com

Abstract. The rapid development of intelligent manufacturing has led to the rise of networked integration of measurement and control (M&C) systems. These systems are crucial for real-time production data, precise control, and product quality assurance. Traditional M&C systems struggle to meet the high requirements of intelligent manufacturing, requiring the integration of technologies like big data, cloud computing, IoT, and 5G. This trend enables seamless data interaction between equipment and systems, in-depth data analysis, and improved production decision-making. This paper explores key technologies and development trends in networked integration of M&C systems for intelligent manufacturing, identifying core technologies like network communication, data fusion and processing, and system integration. The research questions focus on their application in various intelligent manufacturing scenarios and existing challenges.

Keywords: Intelligent manufacturing, Measurement and control system, Networked integration, Network communication, Data fusion

1. Introduction

Intelligent manufacturing is revolutionizing the global industrial landscape, transforming traditional production models and ecosystems. With the implementation of Industry 4.0 and the Industrial Internet, it has integrated into every aspect of production, requiring higher requirements for measurement and control systems [1]. Traditional measurement and control systems are no longer sufficient for modern production needs, making networked integration of M&C systems an important research direction [2]. Research has shown that networked integration technologies significantly improve production efficiency and product quality. For example, the intelligent production line for windbreakers at Ji Hua 3502 Company has achieved a comprehensive digital upgrade by introducing IoT technologies and intelligent equipment. This paper introduces research methods such as literature review, case study, and expert interview, and proposes research questions and significance. The literature review method collects academic achievements in networked integration technologies and intelligent manufacturing, while the case study method analyzes typical corporate application cases to reveal commonalities and differentiated characteristics. The expert interview method involves in-depth interviews with scholars, corporate technical leaders, and

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policymakers to collect insights on technological development trends, industry pain points, and future directions. The research question is how to apply networked integration technologies to intelligent manufacturing to improve efficiency and quality, which is of great theoretical and practical significance for promoting the development of intelligent manufacturing [3].

2. Basics of intelligent manufacturing and measurement and control systems

2.1. Overview of intelligent manufacturing

Intelligent manufacturing, a novel production paradigm, integrates advanced information, manufacturing, and intelligent technologies, distinguished by its automation, intelligence, and informatization features [4]. Its development process can be divided into the initial stage, the development stage, and the maturity stage. In the initial stage, intelligent manufacturing technologies were mainly applied in large enterprises. For instance, automotive manufacturing leaders implemented robotic automated production lines and rudimentary information management systems, resulting in a substantial boost in production efficiency. During the development stage, intelligent manufacturing technologies gradually spread to more enterprises, and small and medium-sized enterprises also began to introduce intelligent equipment and industrial internet platforms. For example, some electronic manufacturing companies optimized their production processes and reduced production costs by introducing intelligent warehousing systems and automated assembly lines. In the maturity stage, intelligent manufacturing will become the mainstream production model, and the entire industrial chain from raw material procurement to product delivery will achieve intelligent collaboration, with highly automated and intelligent productions [5].

Upon grasping the development trajectory of intelligent manufacturing, this paper delves further into its system architecture, a critical aspect for comprehending its functionality in real-world production. The architecture of an intelligent manufacturing system mainly includes the perception layer, the transmission layer, and the application layer. The perception layer consists of various sensors used to collect production data [6]. For example, in a production workshop, temperature sensors can monitor the operating temperature of equipment in real time to ensure that the equipment runs within a safe temperature range. Pressure sensors can monitor the pressure inside pipelines to prevent safety accidents caused by excessive pressure. The transmission layer consists of network communication devices used to transmit data. For example, through industrial Ethernet or 5G networks, the data collected by sensors can be quickly and stably transmitted to the data center. The application layer, made up of diverse application software, is designed for data analysis and processing. Through big data analysis software, for example, production data can be mined in depth to predict equipment failures and optimize production plans, thereby enabling the efficient operation of intelligent manufacturing [7].

2.2. Basics of measurement and control systems

2.2.1. Basic principles and functions of measurement and control systems

A measurement and control system operates on the fundamental principle of utilizing sensors to gather data, which is subsequently processed by controllers to regulate the production process [8]. Its core functions encompass data collection, processing, control, and monitoring. In practical applications, sensors serve as the system's "sensory organs," continuously and instantaneously detecting physical quantities at the production site, including temperature, pressure, flow rate,

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displacement, and more. These sensors convert the detected physical phenomena into electrical signals, which are then transmitted to the controllers. After receiving these signals, controllers will perform filtering, conversion, and analysis to remove noise and interference, extract effective information, and generate corresponding control commands based on preset control strategies. These commands are then transmitted to the production objects through actuators, such as motors, solenoid valves, and frequency converters. This enables precise adjustment and optimization of the production process, ensuring that operations adhere to specified parameters. Concurrently, the monitoring function provides real - time insights into the production process's status. This allows operators to promptly identify any anomalies and take corrective actions, thereby safeguarding the stability and safety of the entire production process.

2.2.2. Differences between traditional measurement and control systems and intelligent manufacturing-oriented measurement and control systems

Under the wave of the vigorous development of intelligent manufacturing, measurement and control systems are undergoing profound changes. There are significant differences between traditional measurement and control systems and intelligent manufacturing-oriented measurement and control systems in terms of architecture, connection methods, and functional characteristics. Traditional systems predominantly adopt a centralized control model, relying on wired connections, which inherently limit their functionality and scalability. In contrast, intelligent manufacturing-oriented measurement and control systems adopt a distributed architecture, relying on industrial Ethernet and IoT technologies to achieve equipment interconnection and real-time data exchange [9]. These modern systems integrate high-precision sensors with intelligent algorithms, facilitating the dynamic adjustment of production parameters, thereby enhancing product quality and production efficiency [10]. Relying on advanced technologies, intelligent manufacturing-oriented measurement and control systems integrate high-precision sensors and intelligent algorithms. High-precision sensors can more accurately collect various data from the production process, providing a more reliable basis for production control. Intelligent algorithms can perform real-time analysis and processing of these vast amounts of data, automatically adjusting production parameters according to production conditions. For example, in the photolithography process of electronic chip manufacturing, real-time monitoring and intelligent adjustment of exposure time and light intensity can significantly improve chip manufacturing accuracy and yield, thereby enhancing product quality and production efficiency. This intelligent approach renders the production process more agile and efficient, aligning seamlessly with the stringent requirements of intelligent manufacturing for precise control and rapid process adaptation.

3. Key technologies for networked integration

3.1. Network communication technology

Communication technologies are crucial in modern measurement and control systems. Industrial Ethernet offers high-speed, stable, and reliable network communication, connecting sensors, controllers, and actuators in smart factories for real-time monitoring and control. In automotive manufacturing plants, thousands of sensors are integrated via industrial Ethernet for precise process control. Wireless technologies like 5G and Wi-Fi 6 provide flexibility and scalability, enabling remote operation of production equipment in hazardous environments. 5G enables ultra-low latency for real-time control commands and motion feedback, while Wi-Fi 6 supports connectivity of mobile

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devices like Automated Guided Vehicles (AGVs) and handheld terminals within factories. These technologies form a comprehensive communication infrastructure for intelligent manufacturing, enhancing safety and efficiency in hazardous environments.

3.2. Data fusion and processing technology

Methods for multi-source data acquisition and fusion mainly include data preprocessing, data fusion algorithms, and data fusion architectures [8]. ensures the cleansing and standardization of raw data, while fusion algorithms reconcile preprocessed datasets into coherent information. These processes are orchestrated by data fusion architectures, which systematically integrate heterogeneous data streams [7]. After understanding the important components and their respective functions of multi-source data acquisition and fusion methods, it is clear that these methods lay a solid foundation for subsequent data processing. However, in practical measurement and control application scenarios, it is not enough to simply complete data acquisition and fusion. More importantly, it is necessary to deeply mine and apply these processed data, which requires the support of data processing algorithms, such as big data analysis and artificial intelligence algorithms, which are increasingly playing an important and extensive role in the field of measurement and control[6]. For instance, big data analysis can be used to analyze the collected production data to identify potential problems and optimize the production process. In the intelligent manufacturing process, production equipment and sensors generate a large amount of real-time data, which contains rich information, such as the operating status of equipment, the quality characteristics of products, and the potential laws of the production process. Complementing big data approaches, AI algorithms facilitate adaptive control strategies by enabling systems to learn from historical data and dynamically adjust operational parameters [3]. This synergy between data fusion methodologies and intelligent analytics underscores the evolution of modern measurement and control systems toward autonomous decision-making capabilities.

3.3. System integration technology

Hardware and software integration are pivotal for intelligent manufacturing. Hardware integration encompasses the seamless combination of sensors, actuators, controllers, and other devices [5]. For instance, in a smart factory, integrating sensors with controllers enables the automatic control of production equipment [4]. On the software side, integration primarily involves measurement and control software, industrial internet platforms, and other applications [9]. When measurement and control software is integrated with industrial internet platforms, it allows for the real - time monitoring and management of the production process [10].

4. Applications of networked integration technologies in intelligent manufacturing

4.1. Applications in smart factories

In smart factories, networked integration technologies can achieve real-time monitoring and control of the production process [1]. By integrating sensors with automated controllers, these systems facilitate autonomous adjustment of production parameters, thereby enhancing operational efficiency and product quality [2]. Beyond automation, networked integration technologies also enable visual management of the production process. Operators can view the operating status of production equipment, production progress, product quality, and other information in real time through monitoring terminals, and promptly identify and resolve problems that arise during the

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production process. Some smart factories have also introduced virtual reality (VR) and augmented reality (AR) technologies, enabling operators to remotely monitor and operate the production process in a more intuitive manner through VR or AR devices, further enhancing the intelligence level of the production process.

4.2. Applications in smart logistics

Networked integration technologies are revolutionizing smart logistics through real-time monitoring and adaptive scheduling optimization of logistics equipment [5]. Central to this transformation is the seamless integration of sensors and controllers, which form a cyber-physical system capable of autonomous decision-making [6]. Sensors, deployed across logistics infrastructure, employ diverse sensing principles to capture critical operational parameters. For example, temperature sensors sense the heat changes generated by the operation of equipment such as motors through thermistors or thermocouples and convert them into electrical signals. These sensors convert physical phenomena into electrical signals, enabling continuous equipment health monitoring. Upon signal acquisition, controllers process data through preconfigured algorithms to assess operational status. Anomalies trigger automated responses, such as motor speed adjustment, conveyor belt recalibration, or emergency shutdowns, preventing fault propagation. This closed-loop control mechanism ensures system resilience and operational continuity. Advanced implementations leverage predictive analytics to forecast potential failures, enabling preemptive maintenance and resource allocation. By minimizing downtime and optimizing throughput, these technologies significantly enhance logistics efficiency, underscoring the transformative impact of networked integration in modern supply chain management.

5. Existing problems and challenges

5.1. Technical issues

The widespread application of networked integration technologies in smart logistics and intelligent manufacturing brings many conveniences but also poses some technical challenges. First and foremost, network security is a key issue that urgently needs to be resolved [9]. With the networking of logistics systems and production equipment, a large amount of production data is transmitted between devices, significantly increasing the risk of data leakage and network attacks[10]. In smart factories, for instance, hackers may target production data, resulting in the leakage of corporate trade secrets. Additionally, the control systems of production equipment are vulnerable to network attacks, which can lead to equipment malfunctions or even production halts. Furthermore, compatibility issues between different devices and systems also restrict the further development of networked integration technologies. Logistics and production systems often contain a variety of equipment from different brands and models, which may use different communication protocols and data formats, making it difficult to achieve seamless connection and data interaction between devices. For example, the warehouse management system and transportation management system of a logistics company may come from different suppliers with inconsistent data formats, preventing real-time information sharing and reducing overall logistics efficiency[1].

5.2. Application challenges

The mplementation of networked integration technologies confronts a series of formidable challenges. Chief among these is the high cost of implementation, which poses a significant barrier

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for small and medium-sized enterprises [2]. The implementation of networked integration technologies requires a significant investment in hardware equipment, such as sensors, controllers, and network communication devices, as well as professional software support and system integration services. For example, a small logistics company may need to spend hundreds of thousands of dollars on purchasing and installing equipment to achieve networked integration of its warehousing equipment, which is a considerable expense for enterprises with limited funds. In addition to financial constraints, the shortage of professional talent also affects the application and maintenance of the technology[4]. Networked integration technologies involve knowledge from multiple fields, including network communication, automated control, and data analysis, requiring professionals with interdisciplinary backgrounds to operation and maintenance. However, there is currently a relative shortage of such professional talent in the market, which leads to many difficulties for enterprises in applying the technology. For example, the lack of professional network communication engineers may lead to network configuration errors during equipment networking, affecting the normal operation of the system [5]. Similarly, a lack of data analysts may impede enterprises from leveraging the wealth of collected data to drive intelligent decision-making processes.

6. Conclusion

This paper delves into the networked integration technologies of measurement and control systems in intelligent manufacturing, elucidating their pivotal roles in improving production efficiency, enabling seamless equipment interconnection, and promoting intelligent decision-making. Networked integration technologies, as a key support for intelligent manufacturing, can effectively integrate production resources and optimize production processes, providing strong technical support for the transformation and upgrading of the manufacturing industry. Despite presenting a comprehensive theoretical framework and exploring the application prospects of networked integration technologies, this research has several limitations. Firstly, this paper lacks in-depth analysis of specific application cases. Although the principles and advantages of networked integration technologies are discussed at a macro level, the practical application effects and implementation details of the technology in actual production are not explored in combination with real corporate cases. This limitation makes the practical guidance of the research somewhat insufficient and fails to intuitively reflect the actual application value of the technology. Secondly, the examination of potential challenges during technology implementation, such as network security threats and equipment compatibility issues, is insufficiently in-depth. The paper fails to offer targeted solutions to address these critical concerns, leaving gaps in the overall understanding of how to overcome practical obstacles in adopting networked integration technologies. Future research will focus on improving networked integration technologies in intelligent manufacturing. In-depth surveys and case studies will analyze their implementation, problems, and solutions. Technical details, such as network security and equipment compatibility, will be explored for more effective solutions. Talent training mechanisms will be improved, as networked integration technologies require multidisciplinary knowledge and professional talent. Targeted training courses and practical projects will be developed to cultivate proficient technology and management professionals. This will provide theoretical support and technical guarantees for high-quality intelligent manufacturing development.

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