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Advancing Intelligent Manufacturing in the Automotive Industry for Enhanced Innovation and Sustainability of New Energy Vehicles

Zheyu Liu[1*]

[1]HNU College of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan, 410082, China

Abstract. Intelligent manufacturing technology is revolutionizing the production processes in the automotive industry through enhanced efficiency, flexibility, and intelligence. This review examines the current applications and future trends of intelligent manufacturing in the automotive sector, aiming to inform technological innovation and strategic planning. The paper begins by outlining the development and significance of intelligent manufacturing in the context of the automotive industry. Key technologies such as the industrial Internet, mechatronics, industrial robots, and digital factories are then highlighted, with an analysis of their roles in improving manufacturing efficiency and product quality. Through a comprehensive literature review and case analysis, the integrated application of these technologies is explored, particularly their innovations in production line design and impact on new energy vehicles. The paper concludes by summarizing how intelligent manufacturing technology is driving the automotive industry's transformation towards greener and smarter production, and it proposes future research directions and addresses technical challenges.

1 Introduction

With the rapid advancement of globalization, informatization, and intelligence, intelligent manufacturing stands as the core and vanguard of the Fourth Industrial Revolution, driving comprehensive transformation and upgrading within the manufacturing sector. This paradigm shift is not merely a technological innovation but represents a fundamental change in industrial structure and production methods. In China, intelligent manufacturing is a critical component of the "13th Five-Year Plan" and "14th Five-Year Plan" and forms the core of the "Made in China 2025" strategy, crucial to the country's manufacturing power agenda.

The automotive industry, a vital pillar of both China's and the global economy, is increasingly oriented towards low-carbon and intelligent solutions due to technological advancements and a global emphasis on environmental protection and sustainable development. The demand for automobiles, particularly new energy vehicles (NEVs), is

* Corresponding author: zheyuliu@hnu.edu.cn

surging, making NEVs the preferred choice for many consumers. Consequently, the production and manufacturing of automobiles, especially NEVs, have reached unprecedented levels of prosperity.

In this context, it is imperative to explore how intelligent manufacturing can enhance the automotive industry, particularly in NEV production, to improve efficiency, reduce costs, enhance quality, minimize pollution, and accelerate innovation and development. This article focuses on the integration of intelligent manufacturing in automotive production, especially NEVs, by summarizing and analyzing existing research and technologies. It discusses the associated challenges and opportunities and provides insights into future developments.

2 Background and analysis of automotive intelligent manufacturing

Intelligent manufacturing integrates advanced manufacturing technology with new-generation information technology, artificial intelligence, and other innovations. It encompasses multiple aspects, including product design and production process optimization. Utilizing mechatronics, industrial robots, big data, the Internet of Things (IoT), and artificial intelligence, intelligent manufacturing achieves comprehensive optimization and represents a new stage in the transformation and upgrading of the manufacturing industry. This approach is based on digital, networked, and intelligent technologies, integrating advanced manufacturing systems to achieve automated, flexible, and efficient production. Key components include automated production, data-driven decision-making, networked collaboration, intelligent control, customized production systems, and full-process quality control [1].

In the field of new energy vehicles (NEVs), research focuses on pure electric vehicles and fuel cell vehicles, with an urgent need to reduce the cost and improve the performance of power batteries. Developing new batteries, enhancing the intelligent manufacturing of power batteries, and improving testing methods and standard systems are critical tasks in NEV development. NEVs must achieve low carbonization in energy use and intelligence in their usage and manufacturing processes. Energy and environmental concerns drive the development of intelligent manufacturing for NEVs [2].

Recent years have seen a rapid increase in NEV sales, attracting numerous companies to the market. However, this surge has also exposed manufacturing challenges, such as the need to improve production efficiency and safety quality. Intelligent manufacturing offers solutions to these problems. To realize intelligent manufacturing of NEVs, companies must accelerate transformation and upgrading, adopt advanced production models, and plan smart factories, focusing on system integration and data governance [3]. This transformation requires coordinated development between enterprises and intelligent manufacturing suppliers to complete the industrial chain's upgrading gradually.

The key to realizing intelligent manufacturing for NEVs lies in the research and application of related technologies. Through artificial intelligence and machine learning, technologies such as machine vision, automatic control, optimization, and intelligent collaborative robots can be realized. IoT technology enables sensor integration, remote monitoring, operation, and intelligent supply chain management [4]. Cloud computing and big data technologies facilitate cloud collaboration, resource sharing, big data analysis, optimization, and simulation and prediction of intelligent manufacturing processes. Promoting these technologies will lead to significant advancements in production efficiency, product quality, and sustainability [5].

In the intelligent manufacturing of automobiles, the application of advanced technologies is crucial for optimizing production processes, improving product quality and safety, reducing production costs, and enhancing production efficiency, thereby increasing market competitiveness. In the highly competitive NEV market, outdated production technologies weaken the competitive position of automotive companies. This article provides a detailed and comprehensive analysis of key technologies and their applications in the intelligent manufacturing of automobiles, offering a deeper understanding of this critical field

3 Automobile intelligent manufacturing technology and application

3.1 Industrial internet

The Industrial Internet represents a new infrastructure, application model, and industrial ecosystem deeply integrated with next-generation information and communication technologies and the industrial economy. By comprehensively connecting people, machines, objects, and systems, it creates a new manufacturing and service system that spans the entire industrial and value chains. This system enables the digitalization, networking, and intelligent development of industries, serving as a cornerstone of the Fourth Industrial Revolution.

From the perspective of integrating manufacturing and services, the Industrial Internet encompasses productive and manufacturing services. By introducing the four perspectives of business, use, function, and realization, it provides a comprehensive framework for integrating manufacturing and services in industrial contexts. This framework offers automotive intelligent manufacturing enterprises a high-quality integration environment and corresponding technical system, significantly enhancing their core competitiveness [6].

A crucial component of the Industrial Internet is the Industrial Internet of Things (IoT), which shares a high degree of technical overlap with automotive intelligent manufacturing. The IIoT involves the integration of various acquisition and control sensors or controllers with capabilities for perception and monitoring, along with mobile communications, intelligent analysis, and other technologies throughout the industrial production process. This integration substantially improves manufacturing efficiency, product quality, reduces costs, and resource consumption, ultimately achieving the transformation of traditional industries to intelligent ones.

In intelligent automobile manufacturing, the effective use of IoT technologies—such as multi-protocol analysis, heterogeneous interconnection, and high-speed data storage and processing—can ensure the successful implementation of intelligent manufacturing processes. These technologies enable automobile companies to achieve transformation and upgrading, leveraging the support of advanced IIoT capabilities [7]

3.2 Mechatronics

Mechatronics is a comprehensive technology that integrates mechanical engineering, electrical and electronic engineering, microelectronics, information technology, sensor technology, interface technology, signal conversion, and other related fields. It is essential to modern automatic production equipment, making it highly relevant to intelligent automotive manufacturing. Technologies such as numerical control (NC), sensor technology, and industrial intelligent robotics are pivotal in combining mechatronics with intelligent manufacturing. These technologies offer high efficiency, flexibility, and precision, significantly enhancing the flexibility and accuracy of automotive manufacturing, reducing labor costs, and improving production efficiency and product quality [8].

Among the various components of mechatronics, numerical control technology and sensor technology are particularly crucial for modern automotive intelligent manufacturing, which demands increasingly higher levels of intelligence. For instance, NC processing technology allows for optimal control of raw materials based on the production characteristics of automotive parts, thereby reducing production costs for automotive enterprises. In the actual production process, sensor equipment based on fiber grating technology provides an excellent reference for verifying whether automotive parts meet engineering standards before shipping.

The practical application of these mechatronics technologies in intelligent automotive manufacturing not only boosts production efficiency for automakers but also expands the practical potential of modern intelligent manufacturing technology. This integration provides a significant advancement for China's intelligent manufacturing industry, offering both enhanced efficiency and quality in automotive production [9].

3.3 Industrial robots

Industrial manufacturing robots are multifunctional, driven, mechanical intelligent devices specifically designed for industrial applications. These robots can execute automated tasks with minimal or no human intervention through straightforward control mechanisms. The primary working principle of industrial robots involves a combination of manual control and their inherent mechanical power. Industrial robots are characterized by high flexibility and production efficiency. The integration of various technologies, such as camera calibration, machine vision, PLC programming, and hydraulic drive, enables these robots to perform tasks such as handling, welding, spraying, assembly, and inspection with enhanced accuracy, efficiency, and quality. Compared to manual labor, industrial robots offer high repeatability, work efficiency, and reliability. Their intelligent application is a significant driver in transforming the labor-intensive automotive industry [10,11].

Machine vision technology, one of the more recent advancements in industrial robotics, plays an increasingly vital role in automotive manufacturing. The primary applications of machine vision in intelligent automotive manufacturing include guidance and positioning, high-precision detection, intelligent recognition, and intelligent interconnection. Machine vision is a complex technology with high requirements for its system and control algorithms. Compared to human vision, machine vision offers comprehensive advantages. The adoption of machine vision technology effectively reduces production costs, and enhances production efficiency, flexibility, and automation. This technology lays a solid foundation for the electrification, networking, intelligence, and sharing economy in the automotive manufacturing industry, promoting faster, better, and more sustainable development [12].

3.4 Digital factory

Digital transformation in the automotive industry refers to the comprehensive upgrade of internal and external business processes using digital and information technologies to improve production efficiency, accelerate product innovation, optimize user experience, and promote sustainable development. This transformation encompasses production and manufacturing, product development, sales and marketing, and user services. It significantly enhances production and operational efficiency, meets personalized user needs, fosters industrial integration and competition, and supports environmental sustainability.

Key technologies and applications in this transformation include data analysis, artificial intelligence (AI), cloud computing, the Internet of Things (IoT), and autonomous driving. For instance, data analysis and AI enable fault diagnosis and predictive maintenance, user behavior analysis and personalized recommendations, and intelligent manufacturing and supply chain management. Cloud computing and IoT technologies facilitate vehicle data analysis, predictive maintenance, Internet of Vehicles (IoV) connectivity, and remote monitoring and control. Autonomous driving and intelligent transportation systems build upon these technologies to realize advanced applications in autonomous driving and intelligent transport [13].

A practical example is the EVA simulation framework designed using DEVS theory and IoT technology, combined with digital twin planning methods. This allows automotive companies to map the information world to physical entities during factory planning, conduct rapid simulation analysis, and generate key indicators to aid efficient planning and decision-making, thus promoting intelligent and digital transformation [14].

The establishment of smart factories represents another trend in digital transformation. Supported by 5G technology, which offers high speed, low latency, extensive connectivity, and high reliability, smart factories enable the widespread application of automation technology. These factories enhance production efficiency and product quality through automated operations and management. They also collect and transmit production data in real time, analyze and process this data, and promote intelligence and automation in production processes. This results in a more efficient, flexible, and intelligent production model, reducing production costs and improving product quality [15].

4 Design of specific production line links for intelligent automobile manufacturing

To effectively harness intelligent manufacturing technology, it is essential to apply it to specific production line processes. For example, the SAIC Volkswagen MEB new energy production line employs a flexible intelligent scheduling system with intelligent decision-making capabilities, significantly reducing manufacturing costs and enhancing market competitiveness. In the highly competitive automotive industry, the trend towards flexible manufacturing of multiple models is growing. The flexibility of basic production equipment underpins decision-making, and the combination of mathematical optimization and artificial intelligence has proven effective in practical applications [16].

However, current automotive production assembly lines still face issues such as non-lean overall process configuration, unreasonable layout, and resource wastage. Therefore, designing feasible assembly process lean and line balance optimization solutions is crucial. For instance, forming a specialized project management team to optimize line balance can increase the value-added time ratio, adjust processes, and optimize layout configurations. These lean improvement solutions not only address existing problems but also significantly enhance production efficiency and reduce production costs [17].

4.1 Automobile inspection and maintenance

Inspection and maintenance are crucial for ensuring automobile quality and safety. Vehicle inspection lines are divided into several modules, including the inspection of interior and exterior parts, vehicle operation performance, electronic and electrical calibration, safety performance, sealing, vehicle driving, abnormal noise, and the distribution and delivery of accompanying items. With the advent of Industry 4.0, vehicle inspection requirements have become more stringent, emphasizing the standardization of technical foundations, intelligent equipment, digitization, and the establishment of control networks. This necessitates the reasonable use of machine vision systems, such as optoelectronic technology and image processing, as well as high-precision sensors and equipment networking [18].

Electronic diagnostic technology exemplifies this advancement. It enables real-time monitoring and fault diagnosis of each electronic control unit (ECU) in new energy vehicles. By connecting a dedicated diagnostic instrument to the on-board diagnostic interface, various parameters and fault codes are read from the ECU and compared with standard values to determine the presence of faults. Common electronic diagnostic methods in new energy vehicles include the OBD on-board diagnostic system, CAN bus diagnosis, BMS battery management system diagnosis, and motor controller diagnosis. These methods provide high accuracy, specialization, real-time feedback, rapid response, flexibility, and adaptability. They offer a more efficient and accurate maintenance method for intelligent automotive manufacturing, significantly improving vehicle maintenance quality and reducing maintenance costs [19].

4.2 Automobile welding

Welding technology is pivotal in the production of new energy vehicles (NEVs), directly impacting the quality and performance of the entire vehicle. Common welding technologies include laser welding, robot laser welding, automated welding, plasma arc welding, resistance welding, brazing, solid-state welding, and friction stir welding [20].

Laser welding, an advanced technology integrating optics, mechanics, and electronics, offers several advantages over traditional methods, such as high energy density, fast welding speed, low welding stress and deformation, and excellent flexibility. Laser welding processes for automotive bodies include laser deep fusion welding, laser wire welding, laser brazing, laser-arc hybrid welding, and more advanced methods such as laser spot welding, laser oscillating welding, multi-laser beam welding, and laser flight welding. With the integration of artificial intelligence in manufacturing, intelligent welding technologies like weld tracking and online defect detection have become essential in automotive body welding, fostering the concurrent development of welding processes and intelligent technologies [21].

Friction stir welding (FSW) is particularly advantageous for welding the lower shell of NEV batteries. FSW uses a cylindrical stirring head rotating at high speed to induce thermoplastic deformation, forming a weld. By optimizing welding process parameters and connection methods, FSW demonstrates excellent performance in product quality, welding speed, energy saving, and environmental protection, offering significant benefits to automotive companies [22].

4.3 Car battery assembly

As the primary energy storage device for new energy vehicles (NEVs), the performance of the battery module is crucial in determining the vehicle's economy, power, and safety. Consequently, the manufacturing and assembly of batteries require special attention in intelligent manufacturing processes. The application of intelligent manufacturing assembly technology ensures the stability of the power battery module's internal structure and necessitates accurate workstation division and assembly time estimation. This approach maintains the module components in a stable capacity state during discharge, extends the physical battery's service life, and ensures the power supply's reliability, thereby enhancing vehicle safety and quality [23].

For example, in the battery assembly production line for plug-in hybrid vehicles, the process plan includes production line process design, module box assembly, and performance testing. To improve production efficiency and automation, the line employs the MES production system's information production control system. The production line is highly automated, allowing the entire power battery pack to be assembled and produced on a single line. Intelligent testing equipment ensures product quality throughout the process. Automation and industrial robotics are extensively used in the assembly process, significantly increasing the production quality and efficiency of battery packs [24].

4.4 Car parts

Automobile parts are fundamental to the integrity and efficient operation of the entire production line. They not only contribute to the overall function and performance of the vehicle but also enable the automation and intelligence of the production process. Therefore, error prevention management of key parts in new energy vehicles (NEVs) is particularly crucial. Automobile companies must employ appropriate error prevention methods and execute corresponding operations based on the complexity of management tasks. This approach minimizes human factors, reduces error rates, and ensures assembly quality [25].

The parts supply chain for NEVs primarily includes batteries, motors, and electronic controls, which are the core components of these vehicles. Strengthening the construction of this supply chain is essential for promoting the high-quality development of domestic NEVs. It is necessary to ensure supply chain stability, select multiple supply channels, and enhance technical research and cost optimization of core parts [26].

For example, the integration of artificial intelligence (AI) in the design of automobile parts packaging systems is transforming traditional packaging systems to meet modern development needs. This transformation includes intelligent parts classification, intelligent packaging solution design, intelligent packaging solution evaluation, and intelligent packaging document management. Through AI technology, a one-stop closed-loop service from packaging demand to design, production, and logistics can be achieved. This improvement in the packaging design system's intelligence level enhances product quality and production efficiency in intelligent automotive manufacturing [27].

5 Conclusion

The application of intelligent manufacturing technology in the new energy vehicle (NEV) industry has demonstrated significant potential and practical benefits. This review highlights that intelligent manufacturing technology not only enhances production efficiency and product quality but also serves as a crucial driver for the industry's sustainable development. Facing future challenges and opportunities, the ongoing development of intelligent manufacturing technology will continue to steer the NEV industry toward a more intelligent, efficient, and environmentally friendly future.

Looking ahead, the application of intelligent manufacturing in the NEV industry will encounter new challenges and opportunities. Future research will focus on innovating production methods and production line design, along with the further development of artificial intelligence (AI) and machine learning technologies. As technology advances, more intelligent applications are expected to emerge, such as adaptive production systems and predictive maintenance. However, the progression of technology also presents challenges, including data security and privacy protection, the complexity of technology integration, and the need for skilled professionals.

To address these issues, targeted policies, research and development, and educational initiatives are necessary. Based on the analysis and review in this article, the future research and development directions of automotive intelligent manufacturing are as follows: To ensure the continued evolution and success of the new energy vehicle (NEV) industry in an increasingly intelligent and competitive landscape, it is essential to focus on several key areas. Strengthening interdisciplinary cooperation will promote the integration and innovation of intelligent manufacturing-related technologies through collaborative efforts. Emphasizing data security and privacy protection by developing and implementing appropriate policies and technical measures is crucial. Enhancing production line flexibility and adaptability will enable quick responses to rapidly changing market demands. Investing in artificial intelligence (AI) and machine learning technologies will improve the adaptability and intelligence of production systems. Additionally, increasing investment in professional talent training is vital to develop programs that cultivate professionals with skills in intelligent manufacturing. By addressing these areas, the NEV industry can continue to advance toward a more intelligent, efficient, and sustainable future.

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