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Research on Automation Technology in Mechanical Engineering within the Automotive Industry

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Abstract: The automotive industry, which has undergone development over the last century, remains a crucial field in the advancement of mechanical engineering. Today, the large-scale production supply chain model has facilitated mass production. In recent years, automation technology has been integrated into multiple vertical sectors of the automotive manufacturing industry, fundamentally transforming the industry's landscape. The combination of industrial robots, intelligent sensors, and complex control systems has significantly enhanced production efficiency and process precision. The ultimate adoption of the flexible manufacturing concept has facilitated the development of modular and intelligent production lines, enabling efficient handling of a large number of different vehicle models. Automation enables core processes such as body welding, painting, and final assembly to optimize their efficiency and workflow, and realizes value in new processes like power battery manufacturing and lightweight material processing. The current technological wave is continuously driving automotive production towards the goal of high efficiency, high productivity, high-quality components, and high flexibility.

1. Introduction

The sector of mechanical engineering automation technology is dramatically changing the automotive manufacturing system. The essential value of mechanical engineering automation technology in automotive manufacture comes from its ability to transcend the constraints of standard production models, allowing for systematic increases in manufacturing accuracy, efficiency, and repeatability. Composite industrial robots, with their excellent repeatable positioning accuracy and excellent load dimensions, economically undertake high-load, high-intensity welding, painting, and precision assembly operations. Integrated smart production lines harness systematically interconnectable data and real-time decision-making systems to dramatically reduce product delivery cycles and variability in the manufacturing process. Instruments of automation technology are finding their way into the optimization of the level of vehicle performance, such that products with the most demanding levels of manufacturing consistency can be made. This is important because manufacturing consistency of the crucial components of a vehicle has a tangible effect on the vehicle's power performance, safety, and durability. The degree of depth and breadth of automation technology application is what is quickly becoming the competitive dimension of the automotive manufacturing sector.

2. The core areas of mechanical engineering automation technology are closely related to the automotive industry

2.1. Basic concepts of automation technology

Automation systems constitute the cornerstone of modern automobile manufacturing, essentially endowing machines with the ability to perform tasks autonomously. Controllers act as the brain of the system, issuing precise commands based on preset programs or real-time inputs. Upon receiving instructions, actuators drive mechanical components to complete specific operations such as welding, handling, and assembly, replacing traditional labor-intensive manual work. Sensors, like keen senses, are distributed throughout the production line, capturing subtle changes in position, pressure, temperature, and other factors in real time and feeding the information back to the controller. These three core components form a closed loop, where the controller processes information and issues commands, the actuators faithfully execute actions, and the sensors monitor the effects and provide feedback for adjustments. Together, they ensure the stable, precise, and continuous operation of the production process, laying an indispensable technical foundation for the large-scale and precision manufacturing of the automotive industry.

2.2. Typical application scenarios for automobile manufacturing

The stamping process in automobile manufacturing demonstrates the shaping of basic forms through automation. Giant presses drive precision molds to repeatedly engage metal sheets, transforming flat plates into door contours with complex surfaces within seconds. Multiple robots on the welding island collaborate to construct the car body frame, with welding guns at the end of the robotic arms moving along three-dimensional paths, welding hundreds of stamped parts into a rigid framework amidst sparking sparks. The painting line maintains a highly clean environment with constant temperature and humidity, where automatic spray guns cover the car body surface at a constant distance and angle, and electrostatic adsorption technology guides the paint mist to adhere evenly, forming a glossy film. The automated logistics system in the assembly area continuously transports large components such as engines and seats, with AGV vehicles shuttling between workstations along magnetic guidance tracks, and mechanical lifting devices precisely aligning the powertrain to the chassis installation points. These automated practices carried out in physical spaces constitute a concrete expression of the modern automobile manufacturing process [1].

2.3. The correlation between automation and the enhancement of automobile performance

The precise alignment of design specifications with automated execution lays the foundation for vehicle performance. The suspension hard point coordinates defined by the digital model are directly converted into robot installation paths, ensuring that the wheel alignment parameters are transmitted to the actual vehicle with millimetre accuracy. In the material processing stage, a laser cutting machine follows the topology optimization contour to cut high-strength steel plates, with the fiber direction precisely matching the requirements of the collision force transmission path. The online measuring arm of the quality inspection system scans thousands of feature points on the body-in-white, and the point cloud data is compared in real-time with theoretical model deviations to locate areas with excessive deviations and guide process compensation. The physical consistency output by these automated processes ultimately precipitates into core performance parameters such as vehicle steering accuracy, high-speed stability, and collision safety, forming a technological closed loop that transforms manufacturing precision into driving experience.

3. The practical challenges faced by the promotion of automotive automation technology

3.1. Cost and barrier to adoption

The equipment procurement process constitutes the first barrier for small and medium-sized enterprises (SMEs) in their automation transformation. Industrial robots and servo systems account for an absolute majority of initial investment, and the price range of a single six-axis robotic arm often reaches the upper limit of a medium-sized enterprise's semi-annual equipment budget. The hidden costs incurred by system integration continue to drive up overall investment, and the design of customized fixtures and joint debugging of production lines consume a significant amount of engineering service resources, with costs often equivalent to 30% to 50% of hardware procurement expenses. The long-term financial pressure brought by maintenance and updates tests the financial resilience of enterprises. Periodic replacement of precision reducers and upgrades of control system versions result in cyclical expenditures, while the loss of production capacity during equipment downtime further magnifies the economic burden. A transformation case study of a component factory in East China shows that the automation upgrade of its stamping line cost tens of millions, and it requires full-load operation for more than five years to offset the investment costs. This high threshold status has led to car companies with annual production volumes of less than 100,000 units generally delaying automation deployment and relying on manual and semi-automatic equipment to maintain basic production rhythms [2].

3.2. Technical compatibility issues

Hardware compatibility issues frequently arise during the renovation of old production lines. Standard robot bases struggle to adapt to the non-standard interfaces of early punch presses, forcing companies to additionally customize adapter flanges and signal conversion modules. Deficiencies in process compatibility hinder the realization of technological value. In a new energy battery tray production line, the workpiece size exceeded the reach of existing robot arms, resulting in the forced downgrade of the automatic grinding unit to a manual workstation. Barriers to data connectivity lead to system collaboration failures. The welding parameter management platform adopts the OPC UA protocol, while the stamping equipment only supports MODBUS communication. Delays in middleware development have resulted in the shelving of the entire line's data traceability function for three months. A case study from the assembly workshop of a joint venture automobile company highlights such contradictions. The introduced intelligent tightening gun failed to read the material parameters of domestic bolts, and the system defaulted to using ultra-high torque settings, leading to a batch of thread slipping accidents. These technological gaps require companies to invest additional resources in secondary development, significantly extending the transition period from installation and debugging to stable operation of automation projects.

3.3. Talent skills gap

The lagging nature of professional education exacerbates the imbalance in industrial talent supply. University electromechanical courses still emphasize traditional machine tool programming instruction, while cutting-edge content such as industrial robot offline simulation and ROS system development has not yet been incorporated into the core credit system. The scarcity of corporate training resources limits the skill upgrading of existing employees. A newly purchased visual inspection system at a central body factory was left idle for two months after equipment acceptance due to a lack of qualified operators, pending on-site guidance from external engineers. The scarcity of interdisciplinary capabilities constrains the operation and maintenance of complex systems.

Personnel with mechanical assembly experience often lack network configuration knowledge and are unable to independently handle production line emergency stop failures caused by packet loss in PLC and robot communication. The practice at a gearbox factory in Southwest China exposed this contradiction, where the automation assembly line experienced delayed fault response due to the separation of mechanical, electrical, and software teams, and a single sensor failure triggered a five-hour production halt across the entire line. This mismatch between technical capabilities and job requirements forces enterprises to pay high outsourcing service fees and continuously undermines the actual operational efficiency and reliability level of automation systems [3].

3.4. Barriers to the integration of emerging technologies

System generational differences hinder the introduction of innovative technologies into existing production lines. Smart tightening guns supporting 5G transmission cannot be connected to the factory's legacy CAN bus network, and real-time data analysis functions are limited by insufficient communication bandwidth and are forced to be downgraded for use. Data architecture gaps delay the deployment process of artificial intelligence. Deep learning models require continuous welding current curve training for defect recognition algorithms, while local SCADA systems only store mean value data at hourly intervals. The lack of a verification system increases the risk of technology integration. When a northern automobile company deployed a digital twin system in its welding workshop, the predicted robot takt time deviated by more than 15% from the actual time due to the virtual environment not simulating electromagnetic interference in the workshop. A battery factory encountered typical difficulties when attempting visual-guided assembly. The laser radar point cloud and CAD model coordinate systems were not unified, and the robotic arm repeatedly misjudged the lamination position, triggering a safety emergency stop. These underlying technological gaps force enterprises to invest additional resources in building transitional interfaces, significantly extending the intelligent upgrade cycle and dampening investment return expectations.

4. Feasible paths to enhance the benefits of automotive automation applications

4.1. Phased technology implementation strategy

The single-point breakthrough strategy guides enterprises to initiate transformation from key bottleneck workstations. A certain car door production line took the lead in replacing pneumatic equipment with servo presses, achieving torque accuracy improvement in the bolt tightening process and accumulating equipment operation and maintenance experience. The local networking stage extends the depth of automation application. The production line subsequently integrates a tightening curve monitoring module, and the screen in the workshop director's office begins to display the fluctuation trend of assembly quality for each vehicle in real time. Global optimization ultimately builds a collaborative manufacturing ecosystem. Its final assembly plant integrates three major data streams: welding, painting, and final assembly to establish a central decision-making pool. The production scheduling system dynamically adjusts order priority based on real-time equipment status. A joint venture factory in South China adopted this path. In the initial stage, it transformed the welding island robots to reduce the repair rate. In the following year, it connected the data from the stamping workshop to optimize the mold replacement rhythm. In the third year, it implemented energy management across the entire factory to reduce peak-to-valley power consumption. The gradual implementation model effectively disperses financial pressure while reducing technical risks and employee adaptation difficulties [4].

4.2. Exploration of low-cost solutions

Modular hardware design reduces the cost of transformation for small and medium-sized production lines. A supplier in the Yangtze River Delta has developed a quick-change robot wrist interface that is compatible with ten types of fixtures, allowing the same robotic arm to alternately complete tasks such as door edging and glass gluing. The open-source software ecosystem reduces system licensing costs, and the control system for a handling robot based on the ROS framework replaces traditional commercial software, compressing the procurement cost of the AGV navigation module to one-third of the original solution. Equipment repurposing activates the value of idle resources. A car lamp factory has converted the spindle of an obsolete CNC milling machine into a rotary gluing station, which, coupled with a second-hand industrial camera, enables automatic inspection of the sealing quality of lamp housings. A parts company in North China has confirmed this approach through practice, replacing servo positioners with PLC-controlled pneumatic fixtures at its welding stations, and running visual positioning algorithms on Raspberry Pi devices. The entire solution costs less than half of an imported system. Such pragmatic innovations significantly alleviate the financial pressure on enterprises and open up an economically feasible path for increasing automation penetration.

4.3. Industry-education integration practice

The curriculum reengineering project has bridged the gap between academic training and industrial needs. A vocational school in Changchun has demolished its traditional machine tool laboratory and established a workstation relying on retired welding robots donated by automobile enterprises. Students' programming tasks are directly related to the optimization of real vehicle body side welding trajectories. The flow of dual-teacher resources has built a skill transfer channel. A provincial electromechanical vocational college has appointed production line technicians as practical course instructors, and the robot maintenance lesson plans they developed cover the latest servo motor overheating diagnosis scheme, which is also used as a troubleshooting manual for teachers during their internships in enterprises. The upgrading of practical carriers has strengthened the ability of technology transformation. An intelligent painting inspection platform jointly built by a school and enterprise in Guangdong replicates the coating defect database of the original vehicle factory. Students debug parameters in a simulation environment to generate optimized schemes, which are directly imported into the actual production line quality control system after being verified by the enterprise. A case study of an eastern vocational education group reflects the depth of integration. Its teaching factory receives the modular transformation of the assembly line eliminated by cooperative automobile enterprises, and students are grouped to implement electrical transformation and PLC upgrade projects. The graduation assessment works become alternative transformation plans for the satellite factory of the enterprise. The deep integration of industry and education continues to provide the industry with technical forces familiar with real production scenarios, effectively bridging the gap in automation talent capabilities.

4.4. Promotion of green automation technology

Optimization of the energy structure drives the carbon reduction transformation of manufacturing processes. A waste heat recovery device deployed in a painting workshop of a car manufacturer captures the heat energy from the exhaust gas of the drying room. The heat exchanger preprocesses fresh intake air to reduce the peak consumption of natural gas. The annual gas settlement statement shows that the proportion of energy supplied by the thermal storage system during the nighttime off-peak period has increased to 40%. The material circulation path reconstructs the value chain of production waste. A stamping factory in East China equips a negative pressure conveying pipeline for metal scraps, which is directly connected to the melting furnace. Aluminum and magnesium alloy scraps are remelted and cast into standard ingots on-site, and then returned to the production line to process new parts, achieving the goal of closed-loop waste management [5]. Digital energy efficiency management improves the precision of resource utilization. The central monitoring system of a final assembly base in Southwest China dynamically adjusts the lighting intensity in the workshop. Smart meters identify standby equipment and automatically cut off power supply during non-production periods. Its annual energy consumption audit report reveals a positive correlation between the decline curve of electricity consumption per unit of output value and the increase in automation coverage. The green practices of a German-funded joint venture factory are exemplary. The roof photovoltaic panels in its welding workshop cover 70% of the area, and the reclaimed water processed by the rainwater collection system is used to replenish the cooling tower. The AGV scheduling algorithm optimizes transportation paths to reduce empty mileage. The Beijing-Tianjin-Hebei parts industry cluster explores a regional collaboration model, with ten enterprises sharing a waste cutting fluid regeneration and treatment center. Professional institutions regularly recycle and filter base oil after removing metal impurities for reuse. These technological practices form reproducible green manufacturing templates, continuously reducing the environmental load throughout the entire life cycle of automobiles [6].

5. Conclusion

The way forward for automation in the automotive industry is full of potential and complications. The initial costs and technological complications means that it is difficult for small and medium-sized enterprises (SME's) to practically consider using automation. Clarity is needed around standardisation for all participants to overcome compatibility challenges in several disparate platforms. Accessing technology potential based upon access to scarce automation talent complicates these circumstances, and large-scale integrating with industrial education will need to be considered to make this possible. The next frontier for enabling inclusive technology will focus upon investigating the potential for modular, scalable and low-cost opportunities. The creation of smarter and adaptive manufacturing contexts built from artificial intelligence and digital twins dynamics. The principles of green automation will direct resource consumption and their environmental footprint as education to be limited. Future automotive industry competitiveness must be scalable based upon responding intelligently to the challenges of automation technology, and with regular engagement with a search for benefits.

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