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Integration of Territorial Intelligence and Triple Balance: Research on the Path of Transformation and Upgrading of Machinery Manufacturing and the Mechanism of Sustainable Development Driven by Informatization

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Abstract: Through the analysis of the inherent problems of "fragmented control", "heterogeneity," and "human-machine separation" of the automation system, it is recognized that the development of hardware automation and software automation is contradictory, and automation technology has changed from "single-point control" to "multi-point control." Technology from "single-point control" to "intelligent whole domain" development path, predictive maintenance, flexible manufacturing, the whole life cycle of the coupled development of digital mapping, to improve the level of fast, accurate and agile manufacturing system, innovation, "low-cost" - low pollution - low humane Low pollution - low humane "three low balance, explore low-carbon manufacturing technology, the whole life cycle of ecological and humane management of sustainable development and construction path. The significance of this research: not only provides theoretical support for the law of intelligent development of machinery manufacturing, more importantly, it provides an operable theoretical basis for the efficiency and sustainable development problems that have been plaguing the machinery manufacturing industry, and is of guiding significance for the high-quality development, green development and intelligent development of the machinery manufacturing industry.

Keywords: informationization drive, intelligent control system, mechanical engineering, sustainable development

1. Introduction

With the development of Industry 4.0 and the Internet of Things (IoT), intelligent control and other technologies have brought revolutionary changes to the field of mechanical equipment management. Based on IoT and big data, Wang developed a full life-cycle management platform for equipment, reducing the emergency non-failure downtime rate (e.g., the inclination of the rack bridge machine) by 60%. Predictive maintenance has proven critical to project safety [1]. In the field of manufacturing, Zhang utilized industrial robots with visual localization and adaptive algorithms for assembly under accurate constraints. However, heterogeneous technology prevents 44% of industrial machines from achieving cross-platform collaboration [2]. Zheng proposed hybrid and remote control technology to realize the integration of human-machine-soft-hardware, forming a "4-stream intersection" (human, machine, soft, hardware, or "4H") model. This improved traditional energy utilization by 28%, but the adoption rate of technologies like AR remains below 20%, and the human-computer miscontact rate still reaches 15% [3].

This paper argues that existing achievements in the field represent only single-point technological breakthroughs (e.g., predictive maintenance, robotic control) and fail to address the core issue of the "imbalance between hardware automation and software intelligence development." Specifically, the lack of a centralized data infrastructure exacerbates technical silos, hindering the realization of comprehensive, domain-wide intelligence. To overcome this, a unified technology platform must be developed to resolve the "perception-decision-execution" challenge—which serves as the foundational objective of this study.

2. Automation analysis of machinery manufacturing

2.1. Technical architecture

The mechanical manufacturing automation control system employs a dual-core framework of "dynamic control + zero system." Within this system, LiDAR control, adaptive algorithms, and real-time deviation correction (achieving trajectory accuracy of ±0.5mm) work in tandem to maximize construction safety at the control level. Furthermore, the IoT-enabled decentralized control platform integrates multiple operations, reducing operational conflicts by approximately 50% [1].

2.2. Efficiency bottleneck

The most pressing challenges in current construction machinery management include management fragmentation, technical incompatibility, and man-machine disconnection. Traditional equipment management systems fail to achieve integrated full life-cycle information for checkability, searchability, statistics, reminders, and traceability, resulting in high equipment idle rates and resource scheduling difficulties due to information fragmentation. More critically, widespread technical incompatibility persists [4], with approximately 44% of systems lacking basic local area networks. Various sensors - including bridge machine wind direction/speed sensors and load measurement sensors - remain incompatible with management platforms, while communication protocol disparities prevent data sharing between systems. This incompatibility prevents real-time IoT data from reaching maintenance platforms, eliminating possibilities for predictive maintenance. Furthermore, man-machine disconnection leads to operational failures (≈15% failure rate) through non-standardized interfaces that don't match actual engineering conditions. Despite their potential, enhanced interaction technologies like AR-assisted assembly and 3D visualization/graphicalization see adoption rates below 20% [5-6].

These issues fundamentally stem from a disconnect between technology implementation and management models. Enterprises often focus on single-technology upgrades while neglecting the crucial "data-system-people" closed loop. For instance, bridge monitoring data remains as raw numerical values rather than being transformed into actionable early warnings, simultaneously increasing failure risks and operator psychological load during information processing. To address these challenges, enterprises should pursue integrated technological transformation by establishing unified data standards to overcome technical barriers, reconfiguring human-factor interaction logic, and achieving true management-technology integration.

3. The development of automation in machinery manufacturing: paradigm shift and technology integration

Automation moves from machine-to-machine to all things intelligent. The direction of the shift is reflected in three aspects.

3.1. Intelligent human-machine collaboration and interaction optimization

The evolution of mechanical manufacturing automation has progressed from individual machine control to intelligent human-machine integrated systems. Jin Yehua emphasized that operational effectiveness must consider human-machine interface ergonomics as a fundamental requirement, advocating for modular design and dynamic visual displays to reduce operational errors (currently at 15%) [6]. Fan Jinling observed that advanced technologies like AR and 3D simulation maintain adoption rates below 20%, stressing the importance of tailoring interaction logic to actual project complexity [5]. A representative case is Wang Jinpeng's transformation of bridge crane monitoring data (including wind speed and lifting capacity) into visualized warning information, effectively reducing cognitive barriers in operations. This approach requires integration with human factors engineering and adaptive interface design, such as permission-based Kanban systems, ultimately establishing an "Information-Warning-Action" workflow to enhance the stability of human-machine collaboration [1].

3.2. Greening and sustainable manufacturing technology integration

Automation technology has made significant contributions to energy conservation, recycling, and environmental sustainability. Zheng Yunxiao demonstrated that hybrid systems can reduce energy consumption in traditional machinery by 30% [3]. Chen Xiaojuan emphasized green material selection and equipment recycling/remanufacturing approaches [4], while Zhang Bin developed energy-efficient assembly line industrial robots with optimized power ratios and implemented 3D simulation for shipbuilding assembly lines to predict and minimize parts matching losses [2]. Future advancements should focus on whole-life-cycle energy consumption monitoring, incorporating IoT-enabled real-time energy sensors throughout the "design-production-recycling" chain. This includes implementing bridge energy consumption information linkage management systems to achieve comprehensive green manufacturing objectives.

3.3. The process of digital integration and predictive maintenance

The development of mechanical manufacturing production automation is advancing toward comprehensive digital integration and predictive maintenance to address information silos and achieve intelligent decision-making closed loops. Current industry challenges include data fragmentation, with Wang Jinpeng's research indicating 44% of enterprises lack local area networks, while heterogeneous systems (e.g., bridge wind sensors and maintenance management platforms) suffer from protocol inconsistencies, creating problematic "information chimneys" that hinder integration and collaboration [1].

Three key technological breakthroughs are enabling progress: First, microservices platforms utilizing databases like MicroService or non-relational CageDB integrate full lifecycle machine data (e.g., bridge crane lifting capacity, wind direction dynamics) into maintenance management platforms, achieving data consensus. Second, IoT technology consolidates equipment vibration and temperature characteristics, enabling diagnostic models with over 90% failure prediction accuracy -

such as preemptively identifying spindle box wear for timely spare parts procurement. Third, virtualization technology enables comprehensive simulation, where virtual machine modeling of equipment stress can replace costly physical trials, while standardized modular CPU interfaces support flexible production.

Looking ahead, the industry will develop BIM + Beidou-positioning industrial internet systems featuring "sensing (sensors) - cognition (big data models) - action (warning work orders)" capabilities across the entire supply chain. This transformation from passive maintenance to proactive health management is projected to reduce total equipment operation and maintenance costs by 30% throughout the lifecycle.

4. Sustainable development of machinery manufacturing

Sustainable development has become the core focus and key challenge for the machinery manufacturing industry. To achieve sustainable development, the industry is integrating intelligent technologies and information technologies such as resource management systems, environmental management solutions, and sustainable management technologies. This transformation is being realized through the application of Industrial Internet of Things (IoT), data mining, and artificial intelligence to enable comprehensive management of manufacturing processes. For instance, predictive maintenance systems allow early detection and prognosis of equipment conditions, enabling proactive maintenance to prevent unexpected downtime and reduce material waste. Additionally, hybrid power technologies in machinery manufacturing have demonstrated the potential to significantly reduce fossil fuel consumption while simultaneously decreasing exhaust emissions and wastewater output [3,5].

The concept of green manufacturing encompasses the entire product lifecycle, including eco-friendly design, sustainable production processes, and effective recycling systems. Intelligent control systems enhance production quality while enabling material reuse and waste reduction. Industrial robots optimize assembly operations to minimize material loss, while advanced recycling technologies facilitate equipment regeneration and extended product lifespans. These approaches collectively contribute to more sustainable material utilization throughout the manufacturing value chain.

A robust support system is essential to guarantee sustainable development in the industry. Current challenges include inadequate professional training mechanisms and outdated management practices. To address these issues, it is crucial to establish cross-disciplinary talent development programs that strengthen expertise in professional knowledge, IT systems, and environmental protection. Furthermore, creating standardized intelligent big data platforms can significantly improve resource management efficiency. Policy support for green technology innovation, including funding for low-carbon equipment research and development, also plays a vital role in driving sustainable transformation.

In conclusion, the machinery manufacturing industry must prioritize technological innovation as its foundation and driving force. By focusing on intelligent system upgrades, ecological impact reduction, and environmental protection measures, the industry can achieve harmonious integration of economic benefits, environmental sustainability, and social responsibility. This three-dimensional approach will provide enduring momentum for the industry's efficient and sustainable development in the long term.

5. Conclusion

This paper analyzes the role of informatization and intelligent control in mechanical engineering and its significant impact on the sector's sustainable development. It proposes transforming mechanical engineering manufacturing automation from "single-machine automation" to "total domain automation," implementing intelligent control technologies represented by human-machine integration (AR and adaptive interfaces), green manufacturing (hybrid power and lifecycle energy monitoring), and comprehensive digital integration with predictive maintenance. The study also identifies multiple obstacles in this automation transformation, including "fragmented governance," "heterogeneous technologies," and "human-machine separation," which fundamentally stem from the imbalance between hardware automation and software control, along with the lack of a closed "data-system-people" loop.

The research's primary contribution lies in proposing a triple-balanced sustainable development framework of "resource-efficient, environmentally friendly, and ethically safe" solutions. This approach enhances manufacturing system efficiency and flexibility through IoT-enabled predictive maintenance and modular elasticity while reducing environmental impact via green manufacturing (material/equipment optimization), remanufacturing, and low-carbon energy technologies. Crucially, it incorporates human-factor ethics through "human-centered" interaction technologies that maintain humane system design, preventing technology-induced risks. The paper also addresses future-oriented data governance challenges, particularly cross-platform protocol barriers and data silos that hinder global smart development, advocating for integrated data centers to bridge edge-cloud and device-information gaps.

Furthermore, the study emphasizes the need for circular economy advancements, particularly in enhancing product recycling and regeneration technologies. It calls for designing end-of-life product recycling systems that achieve resource-level remanufacturing, combined with current intelligent human-machine integration trends. Given the current underutilization of AR/VR and other interactive technologies due to backward development appropriateness, the paper recommends developing situational awareness adaptive operating guidelines and cognitive load adjustment mechanisms to ensure technology serves human actions rather than vice versa. These solutions address three critical challenges in intelligent greening of machinery manufacturing.

In conclusion, the deep integration of automation and IT serves as the core competitiveness booster for machinery manufacturing enterprises, while human-oriented green technologies guarantee sustainable development. This research provides valuable insights for addressing contemporary challenges in continuous efficiency improvement and sustainable synergistic development within the sector. It promotes high-quality, high-resilience, and high-capacity mechanical engineering development through advanced digital twins, supply chain interactions, and policy support mechanisms.

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