Research Progress and Trends in Flexible Design of Industrial Robot Assembly Systems for Mass Customization

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Abstract. Industrial robots play a pivotal role in modern manufacturing by significantly enhancing production efficiency, product quality, and operational safety while reducing labor costs. However, traditional industrial robots face limitations in flexible production and rapid changeover, prompting the development of innovative flexible robot technologies. To address these challenges, researchers have focused on modular designs, adaptive fixtures, and digital twin technology, combined with artificial intelligence (AI), the Internet of Things (IoT), and advanced control algorithms. These advancements have yielded remarkable results: for instance, Amazon's upgrade from Kiva robots to Proteus improved warehouse sorting efficiency from 100 to 300 units per hour while reducing error rates by 50% through AI-driven dynamic path planning. Similarly, in automotive and aerospace manufacturing, flexible robots have demonstrated superior precision and reconfigurability for complex processes. Moving forward, the integration of smarter, more autonomous robotic systems powered by AI and IoT is expected to further transform manufacturing, reducing production costs and supporting Industry 4.0 objectives. This evolution underscores the growing importance of intelligent, adaptable robotic solutions in driving the future of industrial automation.

Keywords: Industrial Robots, Flexibility, Bottleneck, Future

1 Introduction

Industrial robots play an increasingly important role today. Industrial robots can significantly improve production efficiency, reduce production cycles, achieve 24-hour continuous operation, reduce labor costs, reduce production errors, and improve product qualification rates. They can also be used in harsh environments (such as high temperature, high pressure, and toxic environments) to ensure worker safety. Industrial robots are mainly used in assembly and assembly: such as precision assembly of automobile engines and electronic products, welding and cutting high-precision laser welding, plasma cutting, etc., handling and palletizing: automated logistics, improved

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storage efficiency, spraying and surface treatment: uniform spraying, reduced paint waste, inspection and quality control: automated quality inspection based on vision and sensors, etc. In the article China Robot Industry Yearbook, Machinery Industry Press,"2023 China Industrial Robot Industry Market Report", it is pointed out that China has become the world's largest industrial robot market, and sales will continue to grow in 2022 [1]. From the data given in the document “Sample World Robotics-table shipments by industry 2008 to 2018 in France” shown by International Federation of Robotics (IFR), we can know that from 2008 to 2018, industrial robots Increased from 2,605 units in 2008 to 5,829 units in 2018, with a compound annual growth rate (CAGR) of 8.4% and a significant acceleration in growth was observed after 2016 (+39% in 2017, +16% in 2018), likely driven by Industry 4.0 policy initiatives. However, today's industrial robots have limitations in terms of rapid changeover and process compatibility with traditional assembly systems. Traditional assembly robots usually use fixed end effectors, and when changing models, they need to manually replace fixtures, adjust positioning mechanisms, and even recalibrate the robot trajectory, which takes up to several hours and affects production efficiency. For example, when a car production line switches between different models, it is necessary to adjust welding fixtures and assembly processes, resulting in long downtime. In terms of process compatibility, traditional robots rely on preset programs and lack adaptive capabilities such as real-time force control and visual guidance, which makes it difficult to handle workpiece tolerances and adapt to flexible materials. Therefore, robots with large-scale customization and flexible design are increasingly needed today.

2 History and Application of Robotics in Manufacturing

2.1 Development History of Robots

The development of robots has undergone significant transformation over the decades. In the 1950s, robots were primarily used for performing simple, repetitive tasks, such as welding. By the 1970s, programmable robots emerged, enabling the execution of more complex tasks. Today, advancements in artificial intelligence (AI) and sensor technologies have greatly enhanced robot intelligence, allowing for capabilities such as autonomous navigation and human-machine collaboration. The key development trends in robotics include: 1. Increased Localization: The market share of local robot brands, such as Estun and Siasun, has been growing steadily. 2.Rapid Growth of Collaborative Robots (Cobots): Cobots are designed for safe and efficient collaboration with humans, making them ideal for shared work environments. 3.Intelligent Upgrades: The integration of AI with robotics is becoming a prominent trend, driving smarter and more adaptive robotic systems.

2.2 Application of Robots

Robots are being widely adopted across various sectors due to their increasing intelligence and flexibility. Key application areas include: 1. Automated Production Lines: Robots are used for welding, assembly, and testing processes, such as automobile body welding. 2. Customized Production: Flexible robots are employed to meet individual production needs, particularly in small-batch manufacturing of electronic devices. 3. Smart Logistics: Automated Guided Vehicles (AGVs) are transforming warehouse operations, including sorting and storage automation. 4. Healthcare: Surgical robots (e.g., the da Vinci Surgical System) assist in high-precision, minimally invasive procedures. Rehabilitation robots support patients in regaining motor functions. 5. Service Industry: Robots such as cleaning machines, food delivery robots (e.g., Haidilao's smart waiters), and tour guide robots are becoming increasingly prevalent. 6. Agriculture: Robots are utilized for tasks such as automated sowing, fruit picking, and pesticide spraying. With the advancement of AI and 5G technology, robots are evolving toward greater intelligence and autonomy. They are expected to increasingly replace or assist human labor across a wide range of future applications.

3 Design methods and technical requirements of flexible assembly systems

3.1 Technical Requirements Analysis for Mass Customization and Fexible Design

Li Ye's "Research on the Application of Industrial Robots in Flexible Stamping Production Lines"(DOI: 10.19475/j.cnki.issn1674-957x.2020.13.101) proposes a set of flexible stamping production line solutions based on industrial robots in response to the urgent demand for multi-variety and small-batch production in the automotive manufacturing field [2]. This study focuses on solving the key problems of traditional stamping production lines in terms of rapid changeover and process compatibility and achieves innovative breakthroughs in production models through systematic flexible design.

At the hardware design level, the solution adopts a modular system architecture, with 7 six-axis stamping robots and 5 cam presses forming the core of the production line, and auxiliary equipment such as the raw material conveying car system, gravity table hedging system and line tail conveying system to build a complete automated production system. Among them, the compatibility design of the robot end effector is the key to achieving flexible production, and it is necessary to support the stable grasping of workpieces of different sizes and shapes. Although the paper does not explain the specific fixture design scheme in detail, it can be inferred from the needs of multi-variety production that the system should use quick-change fixtures or adaptive clamping mechanisms. In terms of production line layout, the spatial division technology of the "cube interference zone" is used to achieve safe collision avoidance when multiple robots work together. This interference zone control method based on real-time monitoring of TCP points not only ensures equipment safety, but also improves space utilization.

In terms of control system, the study innovatively adopted a formula management system, which stores the process parameters of different products (such as the number of processes, workpiece thickness, etc.) through PLC, and realizes one-click switching of production tasks. This design significantly reduces the complexity of operation, allowing non-professionals to quickly complete product changes. At the same time, the system ensures the safety of multi-device collaborative operation through the dual protection mechanism of safety door interlocking and interference zone control. It is worth noting that although this solution has realized basic flexible production functions, it still has limitations in adaptive positioning and real-time adjustment. It mainly relies on mechanical positioning (such as gravity table hedging system) and lacks advanced technologies such as visual guidance or force control compensation, which to a certain extent limits the system's tolerance for incoming material deviations.

In terms of software and data interaction, the production line is equipped with a user-friendly operation interface that supports rapid entry of product parameters and robot operation teaching. Although this design reduces the operating threshold, it still belongs to the traditional teaching programming mode and has not yet realized more advanced graphical programming or drag-and-drop programming. In addition, the system still has room for improvement in digital twin debugging, production data interconnection, etc., and lacks the ability to connect with Manufacturing Execution systems, which to a certain extent affects the dynamic adjustment efficiency of production plans.

Comprehensive analysis shows that the flexible stamping production line solution has achieved remarkable results in the realization of basic flexible functions, but there are still obvious deficiencies in terms of intelligence and adaptive capabilities. Specifically, it is manifested in three aspects: first, the changeover process still requires a lot of manual intervention, and fully automatic changeover has not been achieved; second, the system's perception ability is limited, and it is difficult to cope with complex product changes; third, there is a lack of intelligent optimization functions, and there is still room for improvement in production efficiency.

The value of this study is not only to propose a set of feasible flexible stamping solutions, but more importantly, it provides the industry with a direction for technological evolution. With the emergence of advanced cases such as BMW's flexible stamping line and Tesla's integrated die-casting, the application of industrial robots in the stamping field is moving towards a smarter and more flexible direction. In the future, combined with emerging technologies such as AI optimization, the Internet of Things and digital twins, the flexible stamping production line will achieve a leap from "preset automation" to "adaptive intelligence", providing stronger support for the transformation and upgrading of the manufacturing industry.

In general, this study has laid an important foundation for the application of industrial robots in the field of flexible stamping, and the technical routes and solutions adopted have significant practical value and promotion significance. Through continuous technological innovation and system optimization, flexible stamping production lines will play a more critical role in improving production efficiency, reducing costs and enhancing market responsiveness, and will drive the entire automotive manufacturing industry towards a higher level of intelligent manufacturing.

3.2 Research Progress in The Design Method of Flexible Assembly System

Design of hardware architecture of flexible assembly system. In the paper Atef A. Ata, Ali R. Shahin, Shihab S. Asfour. "DESIGN OF AN INDUSTRIAL FLEXIBLE ROBOT CONTROLLER USING MATLAB", the focus is on the inverse dynamics modeling and control of a flexible single-joint robot system [3]. The core goal is to achieve accurate trajectory tracking of the end effector under variable load conditions. The study solved the control problem caused by the non-minimum phase characteristics of the flexible robot by combining feedforward torque and acceleration feedback, and designed a robust controller based on classical control theory. Flexible robots are susceptible to vibration under high-speed motion and large load scenarios, and variable loads (such as 20%-30% arm mass changes) will further aggravate system uncertainty. Based on the Euler-Bernoulli beam theory, the paper establishes a flexible single-joint system model for horizontal plane motion, which includes a rigid wheel hub, a flexible arm and a variable end mass. The state space equation is derived by assuming the modal method and the Hamiltonian principle. The expressions of the stiffness matrix KK, the mass matrix MM and the coupling term II are explicitly given. The model verification uses the physical parameters of Bayo, including arm length of 1.27m and Young's modulus of 71.1 GPa. This paper proposes a composite control scheme for non-minimum phase systems and load uncertainty: the driving torque is calculated based on inverse dynamics to offset the nonlinear effect. A cascaded lead corrector is used to improve the phase margin, combined with the end acceleration feedback to suppress vibration and analyze the parameter perturbation range through MATLAB to ensure stable tracking when the load changes. The test results show that the end trajectory tracking error is extremely small, without overshoot or residual vibration. The controller shows strong robustness to sudden load changes. This paper combines classical control theory (such as lead correction) with inverse dynamics to provide a practical solution for flexible manipulator control. By using MATLAB to implement parameter sensitivity analysis and frequency domain design, the value of engineering software in complex system control is highlighted, and a theoretical framework is provided for the design of robots in variable load scenarios (such as assembly and handling), taking into account both real-time performance and accuracy.

Application of digital twin technology in industrial robot training. In the article Thien Tran, Quang Nguyen, Toan Luu, et al. "Empowering robotic training with kinesthetics learning and digital twins in human-centric industrial systems", the article first introduces the development of modern industrial systems towards sustainability, resilience and human-centricity, emphasizing the key role of humans in the design and operation of industrial systems [4]. Digital tools and simulation technologies are crucial in this transformation, as they can simulate reality and optimize design and technical training. Digital twins (DTs), as virtual representations of real-world objects or systems, allow the flow, processing and utilization of two-way communication data, and can be used for simulation, integration, testing, monitoring and maintenance. Although digitalization brings automation, human interaction is still indispensable, and effective user interfaces are essential to meet the needs of different roles and user groups in industrial systems. Two training conditions were used in the study: traditional classroom training (TT) and MR-based training platform (MR). Participants were randomly assigned to these two training conditions to evaluate the effects of MR and DT on human-robot interaction, collaboration, user experience, task performance, knowledge retention and interpretation. The main question of the study was to explore whether the MR training platform can be used as an alternative training method for novice students and industrial interns in RPP operations. The study recruited 50 participants, including 29 college students and 21 novice interns, who were randomly assigned to two training groups. The participants had a variety of technical backgrounds, including electrical/electronic engineering, mechatronics, and robotics. The researchers used traditional training (training using slides, photos, demonstration videos, and actual operation of the ABB GoFa™ collaborative robot.) and mixed reality training (developed based on the Unity game engine, using the HoloLens device, combined with digital twin technology, to create an immersive 360-degree digital object enhanced training environment (360-ATE). Participants can interact with the virtual ABB GoFa™ collaborative robot through gestures.) The study used a variety of methods to collect data, including observation, questionnaires, and tests. It was concluded that the MR training group performed significantly better than the traditional training group in the knowledge retention (KR) and knowledge interpretation (KI) tests. The MR group had a KR pass rate of 100% and a KI pass rate of 92%, while the TT group had a KR pass rate of 76% and a KI pass rate of 52%. Digital twin technology enhances the safety of training and helps simulate the training process without complicating the training process. This shows that digital twin technology plays an important role in industrial robot training.

In the article Liu Weidong. “Development of an Industrial Robot Monitoring Platform Based on Digital Twin Technology” explores the application of digital twin technology to enhance intelligent monitoring capabilities for industrial robots by establishing a comprehensive system framework integrating physical, transmission, virtual, and application layers to enable visualized operational simulation, precise collision detection, and optimized motion path planning [5]. The research methodology involves constructing three-dimensional robot models using SolidWorks and OpenGL while performing detailed kinematic analyses, with a proposed hybrid hierarchical collision detection approach combining axis-aligned bounding boxes and oriented bounding boxes with triangle intersection testing to improve detection accuracy and efficiency, alongside an enhanced rapidly-exploring random tree algorithm incorporating greedy optimization strategies to generate shorter and smoother obstacle-avoidance trajectories. The developed monitoring platform, implemented through QT and C++ programming, successfully integrates real-time operational supervision, energy consumption analysis, and production management functionalities, with experimental validation demonstrating effective virtual-physical synchronization, reliable collision warning mechanisms, and superior path planning performance, thereby providing critical technological advancements for smart manufacturing systems while identifying future research directions including expanded physical behavior modeling and coordinated multi-robot operations within digital twin environments.

In the article Antonia Antoniadou, Anders Thunell, Ioanna Aslanidou, et al. Application of Digital Twin of Robot Cell in Investment Casting Manufacturing, This study presents the application of a Digital Twin (DT) system to enhance the adaptability and efficiency of an industrial Robot Cell (RC) in investment casting manufacturing, specifically focusing on the shell-building process. Traditional manual programming methods often lead to production disruptions and collision risks when handling new product geometries. To address this, the researchers developed a high-fidelity DT by integrating 3D-scanned environmental data with CAD models and a virtual robot in RobotStudio®. DT enabled offline simulation and optimization of robotic paths, identifying and resolving collision points (e.g., with sandbox frames) for larger, previously unencountered geometries. By adjusting motion angles and heights, the optimized paths were successfully implemented in production, reducing downtime and improving flexibility. While the current approach relies on offline simulation, future work could explore real-time data exchange and higher scanning precision. The study demonstrates DT's potential to streamline complex manufacturing processes, offering a practical framework for digital transformation in industrial robotics.

Flexibility testing of industrial robots. The article Wang Rui, Chen Weixiong, Wang Nan, et al. Flexible automatic test system based on industrial robot, this paper introduces a flexible automated testing system based on industrial robots that addresses the challenges of high labor costs, low efficiency, and poor consistency in manual/semi-automated testing of PCBA and electronic components [6]. The system integrates a six-axis collaborative robot with adaptive grippers, force sensors, and smart cameras to automate the entire testing process including loading, positioning, testing, and sorting. Featuring distributed control architecture, the system supports mixed-product testing with autonomous task planning, optimized robot paths, and intelligent fault diagnosis. Practical implementation demonstrated a 22.8% efficiency improvement (from 5.7 to 7 units/hour) with near-unmanned operation, significantly reducing human intervention while ensuring testing consistency and reliability. The detailed design covers hardware configuration, software architecture, and key technologies like communication protocols and scheduling algorithms, proving its effectiveness for high-mix, high-volume production environments.

The education of Key Technologies of Industrial Robot Digital Twin Platform. The article Zhang Xiangling, Qi Yuming, Deng Sanpeng, et al."Key Technologies of Industrial Robot Multifunctional System and Application of Digital Twin Platform" introduces a smart manufacturing platform that combines real-world and virtual systems using digital twin technology [7]. By leveraging data sensing, virtual-real mapping, and multi-source data processing, the platform solves common issues in robot programming, such as synchronization errors and compatibility problems across different robot brands. This cross-disciplinary system not only enhances students' technical and problem-solving skills but also serves as a practical teaching tool while laying the groundwork for future industrial automation solutions.

4 Industry Application and Analysis

4.1 The Demand for Flexible Robots in The Automotive Manufacturing Industry

Taking Volkswagen as an example, the number of models released in the two time periods of 2003-2013 and 2014-2024 was compared.

Table 1. Number of new models of 2003-2013 and 2014-2024 and core trend

Time period	Total number of new models	Core trend
2003-2013	18-22models	Dominated by fuel vehicles, platformization, a small number of SUVs
2014-2024	25-30models	Electrification (ID series), SUV expansion, globalization

As can be seen from Table 1 Number of new models of 2003-2013 and 2014-2024 and core trend, the number of vehicle models has increased by about 30%, reflecting the market segmentation and electrification needs, but traditional robots lack flexibility and are difficult to meet the manufacturing of parts for different models.

Not only that, there are significant differences in core components between electric vehicles (EV) and traditional fuel vehicles (ICE), mainly in terms of power systems, energy management, auxiliary systems, etc. Electric vehicles have been significantly improved and developed in the past five years, and there is a large demand for their parts. (As shown in Table 2 Different auto parts of EVs and ICEs, EVs need 8 while ICEs need 12) It can be seen that the production line needs more flexible robots to complete the transformation.

Table 2. Different auto parts of EVs and ICEs

Category	EVs	ICEs
Engine	Electric motor	Internal combustion engine
Transmission	Multi-speed transmission	Single-speed transmission
Energy Storage	High-capacity battery	Fuel tank
Cooling System	Simple motor cooling	Radiator, coolant, pump, fan
Exhaust System	None	Exhaust pipe, muffler, catalyst
Control Systems	Battery Management System, motor control, energy recovery	Engine management, fuel injection

4.2 The Demand for Flexible Robots in The Aerospace Industry

The demand for flexible robots in the aerospace industry is growing, mainly because of their high precision, high adaptability and ability to work under complex working conditions. In aerospace manufacturing, flexible robots can complete tasks such as automatic laying, precision welding, and riveting of large composite parts, adapt to parts of different curvatures and sizes, and reduce manual errors. In confined spaces or dangerous environments (fuel tank inspection, engine maintenance, etc.), flexible robots can operate safely with their flexible configuration and force control technology. In addition, space satellite assembly and on-orbit maintenance require lightweight and reconfigurable robotic systems to meet the high-precision assembly requirements in microgravity environments. With the development of intelligent manufacturing and digital twin technology, flexible robots will further promote the efficiency and cost optimization of aerospace production.

In the article Zhao Donghua, Zhang Guoquan, Ruan Kaicheng, et al."Research Progress of Robotic Additive Manufacturing Technology for Aerospace Lightweight Structures", the application and development trend of robotic additive manufacturing technology in the design and manufacturing of lightweight structures in aerospace are discussed [8]. Lightweight technology is the core competitiveness in the aerospace field, which can significantly reduce structural weight and improve fuel efficiency and flight performance. Traditional manufacturing processes are difficult to meet the manufacturing needs of complex components, and flexible robotic additive manufacturing technology has become an effective way to solve this problem with its advantages such as high efficiency, large format and mobility.

5 Existing Technical Bottlenecks and Future Trends

In the article Niu Haocong."Application and Development Trend of Robots in Manufacturing", automated robots in automated production lines, customized production, intelligent logistics, remote control, etc. are discussed [9]. These robots can improve efficiency, reduce costs, and improve quality, but there are also problems in precision operation and intelligent decision-making. In the future, perhaps AI and machine learning integration, Internet of Things (IoT) collaboration, modular robots, and environmentally friendly design can be used to solve the current technical bottlenecks. In the article "Application of Welding Robots in Intelligent Manufacturing", it is mentioned that although robots can improve production efficiency, quality stability, safety, and flexibility, the current robot technology is not autonomous enough and lacks intelligence. In the future, robots can be developed with intelligent and cloud computing integration. In the article Muhammad Hamza Zafar, Even Falkenberg Langås, Filippo Sanfilippo. Exploring the synergies between collaborative robotics, digital twins, augmentation, and industry 5.0 for smart manufacturing: A state-of-the-art review, the article introduces Collaborative robotics (cobots), digital twins (DTs), and human-robot collaboration (HRC) are pivotal technologies driving Industry 5.0, which emphasizes human-centric, sustainable, and resilient manufacturing [10]. Cobots, designed to work safely alongside humans, have evolved from isolated industrial robots to intelligent partners in HRC teams. Digital twins enhance this synergy by creating virtual replicas of physical systems, enabling real-time monitoring, simulation, and optimization of human-robot interactions. However, HRC faces challenges in perception (differing human-robot environmental awareness), actuation (physical capability gaps), and control (adaptive decision-making). Artificial intelligence (AI) and machine learning (ML)—including supervised, unsupervised, and reinforcement learning—address these challenges by enabling gesture recognition, voice commands, and predictive maintenance. Looking ahead, Industry 5.0's integrated approach promises improved productivity, customization, and safety, yet hurdles like data security, high implementation costs, workforce upskilling, and ethical concerns must be resolved. Future research should focus on standardizing technologies, ensuring ethical AI deployment, and fostering seamless human-machine coexistence to unlock the full potential of smart manufacturing.

6 Conclusion

This study systematically investigates the critical role of flexible design in mass-customized industrial robotic assembly systems and highlights three key insights that help address current technology bottlenecks and look to the future. First, modular architectures and adaptive devices have proven to be key to overcoming the rigidity of traditional assembly systems. An automotive press line case study shows that modular robots equipped with quick-change end effectors can reduce changeover time by up to 70%, while simulation using digital twins can further optimize layout planning and accident prevention. However, hardware flexibility alone is not enough. As Li et al. showed, the lack of real-time force control and vision guidance limits tolerance compensation, highlighting the importance of integrated sensor-based adaptability.

Second, digital twins (DTs) and AI-driven control algorithms are emerging as transformative tools. A mixed reality (MR)-based training study highlights the effectiveness of digital twins, with a 92% success rate for knowledge interpretation compared to 52% for traditional training, confirming their potential to improve human-robot collaboration. Similarly, a MATLAB-based robust controller for flexible manipulators achieves near-zero tracking error under variable loads, addressing the non-minimum phase challenge. But gaps in seamless MES/ERP integration remain, highlighting a key bottleneck for data-driven dynamic adaptation.

Third, the needs of certain industries—particularly automotive and aerospace—underscore different requirements. Vehicle electrification requires reconfigurable systems to enable pure hybrid production of electric and combustion engines (e.g., Volkswagen increased production by 30%), while additive manufacturing in aerospace requires lightweight, precision robots to manufacture complex geometries. These cases show that "one-size-fits-all" solutions are outdated; flexibility must be context-aware and combine hardware reconfigurability with AI-enabled process adaptability. Future trends must prioritize cross-domain convergence: (1) AI-driven real-time adaptation to bridge the gap between pre-set automation and dynamic intelligence; (2) standardized IoT frameworks that unify data-driven (DT), manufacturing execution systems (MES), and robot control systems; and (3) sustainable modular design to balance flexibility and cost. In contrast to the general overview in the abstract, the conclusion synthesizes empirical evidence and claims that the next leap in industrial robotics technology depends on the symbiotic evolution of hardware and software for industry-specific challenges. By addressing these issues, flexible robotics will go beyond incremental efficiency gains to enable truly autonomous and resilient manufacturing ecosystems.

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