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Design and Application of Industrial Robots in Electric Vehicle Battery Assembly

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ABSTRACT
With the rapid development of the global new energy vehicle industry, the demand for power batteries has grown exponentially, and traditional production methods can no longer meet the requirements for large-scale, high-precision, and high-efficiency assembly. This paper focuses on the design and application of industrial robots in electric vehicle (EV) battery assembly, aiming to address industry bottlenecks in production capacity and quality control.First, the paper identifies the seven core processes in EV battery assembly and systematically analyzes the characteristics and application scenarios of five types of industrial robots—welding, material handling, assembly, sealing, and inspection—laying the foundation for subsequent design optimization. In terms of robot design, innovations are made from two key dimensions: end effectors and robot body parameters. End Effectors: A "servo motor + curved flexible gripper" optimizes flexible clamping, while integrated pressure, temperature, and vision sensors enable closed-loop control. Additionally, a micro-fastening spindle and glue-dispensing inspection probe are innovatively integrated to achieve "grasping-positioning-fastening-inspection" in one operation. Robot Body Parameters: Optimization focuses on motion accuracy, load capacity, dynamic response, and structural reliability. For instance, high-precision harmonic reducers and 17-bit absolute encoders improve repeatability to ±0.02 mm, modular joint designs adapt to varying load scenarios, and high-power-density motors with carbon fiber-reinforced arms enhance dynamic performance. To validate the design, two case studies are presented: (1) The X2 parallel robot achieves high-speed battery packing at 80–120 cycles per minute with a positioning accuracy of ±0.5 mm, improving efficiency by over 50% compared to manual labor, thanks to its large workspace-to-volume ratio, high dynamic performance, and specialized end effector. (2) In a KUKA robot system integration case, eight robots across three workstations perform tasks such as battery shell welding and deburring, achieving trajectory accuracy below 0.5 mm, a 95% utilization rate, and cost savings from reduced system redundancy. The paper also highlights current challenges, including insufficient flexible production capability, inconsistent precision stability, high costs, and safety risks. Accordingly, four optimization directions are proposed: enhancing flexibility, improving precision stability, reducing costs, and strengthening safety measures.The research ultimately delivers a robot design that balances precision, efficiency, and cost, effectively alleviating supply chain bottlenecks in power battery production and supporting the expansion of the new energy vehicle industry. Looking ahead, deeper integration with digital twin and AI technologies, along with the development of specialized and lightweight equipment, is expected to further advance the intelligence and cost-effectiveness of industrial robots in EV battery assembly.

KEYWORDS
Industrial robot; Battery assembly; End effector; Optimization of robot body parameters

1 Introduction

1.1 Research Background

With the increasingly severe global environmental issues and the transformation of energy structures, electric vehicles, as important carriers of green travel, have witnessed an explosive growth in market demand. According to statistics from BloombergNEF (BNEF), the global installed capacity of power batteries reached 650GWh in 2023, and it is expected to exceed 2.5 TWh by 2030, with a compound annual growth rate of over 25%. This requires large-scale and high-efficiency assembly methods for power battery production, and traditional manual or semi-automated production methods can no longer meet the industry's needs. As the core component of electric vehicles, the performance of power batteries is directly related to the vehicle's driving range, safety, and service life.

1.2 Research Significance

As the global penetration rate of new energy vehicles rises rapidly, the demand for power batteries grows exponentially. This research can design targeted robot application solutions suitable for high-tempo and heavy-load operations, break the production capacity bottleneck of traditional production lines, ensure the accurate matching between battery output and the demand of downstream automakers, and provide core manufacturing support for the continuous expansion of the new energy vehicle industry. The performance and safety of power batteries are highly dependent on assembly accuracy. Through optimizing the robot's motion control, force control feedback, and integration of visual inspection, the research can significantly reduce the errors caused by manual operations, improve the consistency of key processes such as battery tab welding, sealant application, and cell stacking, and reduce potential safety hazards in the later use of batteries from the manufacturing end.

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2 Related Theories and Technical Foundations

2.1 Core Processes of Electric Vehicle Battery Assembly

(1) Cell screening and testing; (2) Cell preprocessing; (3) Cell series and parallel connection; (4) Module assembly and fixing; (5) Battery pack integration; (6) Wire harness connection and fixing; (7) Sealing and shell packaging.

2.2 Types and Characteristics of Industrial Robots

(1) Welding robots: Applied in cell tab welding, module busbar welding, and shell seal welding. Equipped with special welding torches such as laser welding, ultrasonic welding, or resistance welding, with a positioning accuracy of within ±0.05 mm, which can meet the welding needs of battery-specific materials such as copper and aluminum. (2) Material handling and loading/unloading robots: Used for single cell feeding, module handling, and battery pack assembly transfer. They mostly adopt SCARA robots with high precision and speed for small cell handling, or six-axis robots with strong load capacity for heavy-duty module handling; some are equipped with visual guidance systems to achieve accurate positioning and grasping of cells/modules, adapting to flexible production. (3) Assembly robots: Applied in module sampling line installation, BMS (Battery Management System) module assembly, and bolt tightening. Equipped with a tightening shaft with a torque sensor, which can accurately control the tightening torque to prevent component damage due to over-tightening or looseness due to under-tightening. (4) Sealing robots: Used for applying sealing rings on battery pack shells, coating thermal conductive adhesive between cells, and applying sealant between modules and shells. Equipped with high-precision dispensing valves or glue guns, which can control the uniformity of glue dosage and support various types of glues to meet different process requirements. (5) Testing robots: Applied in cell appearance inspection, battery pack air tightness testing, and high-voltage insulation testing. Equipped with visual cameras and sensors, which can quickly identify surface defects of cells with a detection accuracy of 0.1 mm.

3 Key Design Points of Industrial Robots

3.1 Design of End Effectors

End effectors need to be designed according to specific assembly actions, covering 3 core functions to avoid process adaptation deviations. (1) Grasping function: For battery cells or modules, corresponding clamping structures need to be designed to ensure no slippage or collision. (2) Positioning function: Integrate visual guidance or precision positioning pins to ensure the assembly tolerance between the battery and the tray, and between the module and the shell. (3) Auxiliary function: In some scenarios, modules such as terminal tightening, glue application detection, and polarity identification need to be integrated to reduce the switching of multiple devices.

Optimizations are made for these three functions to design more efficient end effectors. (1) Optimize flexible clamping: Adopt a combination of "servo motor + arc-shaped flexible gripper". The contact surface of the gripper is covered with 0.5 mm thick food-grade silica gel. The adjustable range of the clamping stroke is expanded to 80-350 mm, and the clamping force can be steplessly adjusted from 0 to 500 N through a force control algorithm. Compared with the traditional cylinder clamping with a force adjustment accuracy of only ±20 N, it has a wider adjustment range. (2) Optimize multi-sensor integration: Integrate 3 types of core sensors, namely pressure sensors, temperature sensors, and visual sensors. The pressure sensor monitors the clamping force and immediately reduces the force when the threshold is exceeded to form a "perception-feedback-adjustment" closed loop; the temperature sensor monitors the surface temperature of the battery in real time to avoid cell damage caused by high-temperature assembly; the visual sensor recognizes the position of the battery poles and shell defects in real time, with a positioning accuracy of ±0.02 mm. (3) Optimize multi-process integration: Integrate a micro tightening shaft and a glue application detection probe on the side of the clamping body. The torque of the tightening shaft can be adjusted in the range of 0.5-10 N·m. The glue application detection probe judges whether the glue application thickness meets the standard through laser ranging, realizing the one-stop completion of "grasping-positioning-tightening-detection".

3.2 Optimization of Robot Body Parameters

To meet the core requirements of high precision, high flexibility, and high stability in battery assembly, the optimization of robot body parameters focuses on four dimensions: motion accuracy, load capacity, dynamic response, and structural reliability. Combined with different assembly scenarios of prismatic, pouch, and cylindrical batteries, the robot body parameters can be upgraded by improving motion accuracy parameters, load and inertia parameters, dynamic response parameters, and structure and reliability parameters.

(1) Improvement of motion accuracy parameters: Optimize the joint reducer by replacing the traditional RV reducer with a high-precision harmonic reducer. The transmission error of this reducer is ≤1 arc minute, while that of the traditional RV reducer is 3-5 arc minutes. By adjusting the preload force, the preload torque is ±0.5 N·m, and the joint backlash is reduced from 0.01 mm to 0.002 mm. Adjust the servo system by using a 17-bit absolute encoder instead of the traditional 13-bit encoder, which increases the position feedback resolution by 16 times. Combined with the feedforward control algorithm, it can real-time compensate for the position deviation caused by inertial load, and the repeat

positioning accuracy is improved from ±0.05 mm to ±0.02 mm. Upgrade the end flange by adding a laser interferometry calibration interface, which supports online automatic calibration every 300 hours. The traditional flange requires shutdown for manual calibration with a cycle of 7 days, and the long-term accuracy retention rate is increased from 80% to 95%.

(2) Optimization of load and inertia parameters: Optimize the load level by adopting a modular joint design. The rated load of the 6-axis robot can be adjusted by replacing the joint motor to increase the power from 0.75 kW to 2.2 kW, flexibly switching between cell grasping scenarios and module stacking scenarios. Upgrade the inertia matching by optimizing the moment of inertia of the joint motor rotor, reducing it from 0.005 $kg \cdot m^2$ to 0.002 $kg \cdot m^2$. The inertia ratio between the motor and the load is increased from 1:5 to 1:10, avoiding impact vibration when starting and stopping heavy-inertia loads, and reducing the vibration amplitude from 0.1 mm to 0.03 mm.

(3) Optimization of dynamic response parameters: Improve the assembly cycle efficiency by upgrading the joint motor. Adopt a high-power density permanent magnet synchronous motor to increase the power density from 3 kW/kg to 5 kW/kg. The maximum speed of the 6-axis is increased from 300 rpm to 500 rpm, and the joint acceleration time is shortened from 0.5 s to 0.2 s. Optimize the dynamic stiffness by embedding carbon fiber reinforcing ribs in the forearm and upper arm frames of the robot instead of the traditional aluminum alloy frames. The structural dynamic stiffness is increased by 60%, and the first natural frequency is increased from 80 Hz to 128 Hz. When moving at a high speed of 1.5 m/s at the end, the amplitude is reduced from 0.05 mm to 0.01 mm, which not only protects the battery and avoids the deformation of the pouch battery shell but also improves the cycle stability.

3.3 Summary of Core Optimization Values

(1) Accuracy compliance: Meet the requirements of high-precision processes such as pole welding and cell alignment, and reduce the cost of manual secondary calibration.(2) Flexibility improvement: The modular load design is suitable for full-specification batteries, and the model change efficiency is increased by more than 70%.(3) Efficiency upgrade: The optimization of dynamic response increases the production line cycle by 30%, and the single-shift module production capacity is increased from 120 sets to 156 sets.(4) Cost reduction: Improved reliability reduces downtime for maintenance, and the annual maintenance cost is reduced by 40%.

4 Application Cases and System Verification

4.1 Single Process Design Case

Application of X2 Parallel Robot in High-Speed Boxing Process of Electric Vehicle BatteriesIn the high-speed boxing process of electric vehicle batteries, the X2 parallel robot system shows unique advantages. This parallel robot system has a large ratio of working space to volume, good mechanical performance, a simple structure, low production cost, and easy system control. During the boxing operation, first, an accurate kinematic model and inverse dynamic model are established. According to the size and limitations of the batteries and battery boxes, the size of the robot and the structure of key parts are specially designed, and an appropriate transmission system structure and lead screw transmission mechanism are determined.

By analyzing the constraints of the battery and the internal structure of the battery box in the battery grasping operation, a targeted battery grasping scheme and end effector structure are designed. In the actual boxing process, the robot grasps the batteries quickly and accurately according to the planned path trajectory of the moving platform and places them into the battery box. The PC and NI motion control card are used to achieve efficient control, which meets the requirements of speed and accuracy for the high-speed boxing of electric vehicle batteries and greatly improves the boxing efficiency and quality [2].

Advantages of X2 Parallel RobotThe X2 parallel robot system has a large ratio of working space to volume, which enables it to complete a large range of operations in a relatively compact space, making it suitable for scenarios such as electric vehicle battery boxing that require high space utilization. It has good mechanical performance. The parallel robot adopts multi-branch parallel drive, which has no transmission energy consumption and small motion inertia, and can realize high-speed reciprocating operations. Its structure has high rigidity and strong anti-vibration ability, which can meet the requirements of speed and accuracy for the high-speed boxing of electric vehicle batteries. It has low cost and easy control. The simple structure reduces the number of fault points, making daily maintenance convenient and the maintenance cost low. At the same time, its short transmission path and low energy loss result in low energy consumption cost. In addition, the system is easy to control, and efficient control can be achieved by using a PC and an NI motion control card [3].

Design and Modeling of the RobotRelevant studies have established accurate kinematic and inverse dynamic models of the X2 parallel robot, conducted kinematic and dynamic design, and determined the parameters of the servo motor, providing a theoretical basis for the efficient operation of the robot. According to the size and limitations of the batteries and battery boxes, the size of the X2 parallel robot and the structure of key parts are specially designed, an appropriate transmission system structure is determined, and a lead screw transmission mechanism is selected to ensure that the robot can meet the specific requirements of battery boxing. By analyzing the constraints of the battery and the internal structure of the battery box in the battery grasping operation, a targeted battery grasping scheme and end effector structure are designed to ensure that the robot can grasp and place the batteries accurately. In the middle and later processes of lithium battery production, high-speed parallel robots similar to the X2 parallel robot can realize high-speed sorting actions of 80-120 times per minute, with a positioning accuracy of ±0.5 mm, which meets the requirements of speed and accuracy for the high-speed boxing of electric vehicle batteries. Taking a similar intelligent production system as an example, its overall production efficiency is more than 50% higher than that of traditional manual assembly. The X2 parallel robot can also greatly improve the boxing efficiency in the high-speed boxing of electric vehicle batteries, reduce manual intervention, and lower labor intensity and operation errors [4].

4.2 Full-Process System Integration Case

KUKA has developed three systems for a global auto parts supplier to produce various aluminum alloy battery shells. In three KUKA cell4_FSW workcells, eight robots perform tasks in four steps. First, the robots pick up various parts of the bottom plate, weld the bottom plate, and then deburr it; next, the robots weld the frame to the bottom plate; finally, the entire battery box is deburred. In this solution, the utilization rate of the friction stir welding robot is as high as 95%. Under the same production volume, two systems are saved, as well as costs such as personnel and production floor space. Moreover, due to the trajectory accuracy of less than 0.5 mm, high-precision and perfect weld seams can be achieved, meeting the high requirements of battery boxes for air tightness and collision resistance [5].

Performance Advantages of the Robot(1) KUKA's KR FORTEC series robots have high load capacity and high precision. For example, the KR 500 R2830 MT has strong load capacity and can easily handle the handling and operation of various large parts in battery shell production. Due to the adoption of the KR FORTEC 500 R2830 MT with high rigidity and long service life, precise trajectory guidance can be achieved, with a trajectory accuracy of less than 0.5 mm. This is crucial for the production of battery shells that have high requirements for welding accuracy and dimensional accuracy, ensuring the air tightness and structural strength of the battery shells and meeting the strict standards of electric vehicle battery boxes for collision resistance.

(2) KUKA robots have high flexibility, versatility, and multiple degrees of motion freedom, which can realize complex movements and flexibly switch tasks in different processes of battery shell production. From the initial part picking to welding, deburring, and other operations, one robot can complete multiple tasks, reducing the number of equipment and production floor space. One robot in a workcell can operate three tooling fixtures and perform three different welding tasks. This versatility greatly improves production efficiency and the flexibility of the production line [6].

Analysis of Design RequirementsKUKA has developed a system for a global auto parts supplier to produce various aluminum alloy battery shells. Battery shells have extremely high requirements for air tightness and collision resistance. Therefore, high-precision weld seams must be ensured during the welding process, with a trajectory accuracy of less than 0.5 mm; at the same time, under the premise of ensuring production volume, production costs should be reduced as much as possible, and the number of personnel and production floor space should be reduced. From the subsequent application results, the utilization rate of the friction stir welding robot in this system is as high as 95%. Under the same production volume, two systems and related costs are saved, and the weld quality meets the performance requirements of the battery box, fully complying with the design requirements.

5 Existing Problems and Optimization Directions

5.1 Existing Problems

(1) Insufficient flexible production capacity: The new energy vehicle market has a variety of product models, and main engine manufacturers require parts suppliers to shorten the delivery cycle. Traditional rigid production lines are difficult to quickly respond to the production needs of multi-variety and small-batch products. The process parameters and assembly requirements of different types of batteries vary greatly, and traditional single-type robots are difficult to be compatible with multiple production tasks.

(2) Accuracy and stability need to be improved: Power battery manufacturing has strict requirements for accuracy. For example, in processes such as welding and glue application, traditional robots have shortcomings in high-precision perception guidance and high-accuracy quality detection, making it difficult to fully meet the requirements of high-quality production.

(3) High cost: The costs of robot purchase, maintenance, and training are relatively high, which brings greater financial pressure to small and medium-sized enterprises and limits the wider application of industrial robots in this field.

(4) Existing safety risks: During the battery assembly process, there are potential safety hazards such as electrical hazards, thermal injuries, and flammable and explosive substances. The robot itself may also cause safety problems due to software failures, hardware failures, communication failures, etc.

5.2 Optimization Directions

(1) Improve the degree of flexibility: Develop a flexible combination of reconfigurable hardware platforms and process

package software. For example, Atom Robot can adapt to multiple battery models by replacing fixture modules and calling different process parameter packages, shortening the switching time.

(2) Improve accuracy and stability: Apply technologies such as laser welding and visual inspection to improve the robot's precision perception and guidance capabilities. Collect data through the system and establish models to quickly generate new process parameters to ensure product quality.

(3) Reduce costs: Develop lightweight and easy-to-deploy robots to reduce the manufacturing and maintenance costs of robots. At the same time, optimize the production process to improve equipment utilization and reduce overall production costs.

(4) Strengthen safety protection: Strengthen the mechanical safety design in the robot design stage, set up emergency stop buttons, protective devices, etc., to ensure the stability and reliability of the electrical system. At the same time, install an environmental monitoring system to monitor environmental safety in real time.

6 Conclusions and Prospects

This research focuses on the design and application of industrial robots in electric vehicle battery assembly. Through the optimization of core process adaptability, the upgrading of key component parameters, and the verification of practical cases, a set of robot design solutions that balance accuracy, efficiency, and cost has been formed. By optimizing flexible clamping with the combination of "servo motor + arc-shaped flexible gripper", the adjustable clamping stroke of 80-350 mm and the stepless clamping force control of 0-500 N are realized, solving the problems of low clamping accuracy and poor adaptability of traditional cylinders; integrating three types of sensors (pressure, temperature, and visual), a closed loop is constructed with a positioning accuracy of ±0.02 mm, and simultaneous cell temperature monitoring and pole positioning are realized; innovatively integrating a micro tightening shaft and a glue application detection probe, the one-stop operation of grasping-positioning-tightening-detection is completed, reducing the time consumed by switching multiple devices and realizing the functional upgrading of the end effector. In terms of motion accuracy, the use of high-precision harmonic reducers and 17-bit absolute encoders increases the repeat positioning accuracy from ±0.05 mm to ±0.02 mm, shortens the online automatic calibration cycle of the end flange to 300 hours, and increases the long-term accuracy retention rate by 15%; in terms of load and dynamic response, the modular joint design realizes the power switching of 0.75 kW-2.2 kW, which is suitable for cell grasping and module stacking scenarios. The high-power density motor and carbon fiber reinforced arm increase the maximum speed of the 6-axis by 67% and reduce the amplitude of high-speed motion to 0.01 mm, alleviating the problem of insufficient production capacity in the electric vehicle supply chain and contributing to the transformat.In the future, with in-depth technological integration and the construction of an intelligent closed loop, industrial robots will be promoted to combine with digital twin technology to establish a virtual simulation model of the entire battery assembly process, realizing pre-optimization of process parameters and fault prediction. Integrate AI vision and force control perception algorithms to improve the cell defect recognition rate and the real-time adjustment ability of welding force, and upgrade from "automated execution" to "adaptive decision-making". Aiming at the differentiated needs of pouch and cylindrical batteries, develop deformable end effectors and adaptive clamping algorithms; explore the "robot + AGV" collaborative mode to realize the fully unmanned whole process from battery module assembly to storage, and further shorten the production line switching time. Develop lightweight robot bodies (using composite materials to further reduce weight by 30%) and low-power servo systems to reduce the purchase and energy consumption costs of robots; develop standardized process modules to reduce the customized costs of robot deployment for small and medium-sized enterprises and expand the application scope of the technology. Incorporate electrolyte leakage detection and high-voltage protection linkage functions into the robot design to reduce electrical and chemical risks during the assembly process; jointly develop "robot operation + process programming" composite training courses with universities and enterprises to alleviate the shortage of professional talents and provide human support for technology implementation.

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