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Research on Innovative Paths for Automated Mechanical Equipment Installation Management under the Background of Intelligence

Li Houping

Mino Automation Usa Inc., Auburn Hills, Michigan, United States

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Abstract: The installation of automated mechanical equipment is a critical link in the implementation of intelligent manufacturing, and its management quality directly impacts equipment operating precision and production line commissioning efficiency. This paper analyzes new features of automated equipment installation management under the background of intelligence, including compound technical parameters, enhanced process coupling, and refined process control, while identifying major issues such as single installation accuracy control methods, weak data-driven decision-making, inefficient multi-disciplinary cross-coordination, and insufficient process traceability. On this basis, innovative paths are proposed—including digital measurement and accuracy pre-control systems, real-time installation process data acquisition and intelligent early warning, a multi-disciplinary collaborative management platform, and a lifecycle quality traceability mechanism—providing technical reference and practical guidance to improve the installation management level of automated mechanical equipment.

1. Intelligence

Industrial automation equipment is rapidly developing toward high precision, high integration, and high intelligence. Numerical control (NC) machining centers, industrial robots, automated assembly lines, and other equipment are widely used in automotive manufacturing, electronic information, precision machining, and other fields. The installation accuracy and commissioning quality of such equipment directly affect product yield and production line stability; thus, refined and intelligent installation management is a prerequisite for ensuring equipment performance throughout its lifecycle. However, the traditional installation management mode, which relies on manual experience and static inspection, cannot meet the new requirements of intelligent equipment regarding accuracy grades, system joint commissioning, and process traceability. Starting from the background of intelligence, this paper analyzes the main problems existing in automated equipment installation management and proposes innovative and optimized approaches.

2. Theoretical Evolution and Intelligence Requirements of Automated Mechanical Equipment Installation Management

2.1 Examination of Limitations in Traditional Installation Management Modes

Traditional automated equipment installation management is an experience-oriented operational mode where the quality of key procedures—such as equipment positioning, leveling, alignment, and tightening—is judged mainly by the personal experience and tactile feel of installation technicians. Inspections mostly use conventional measuring tools such as dial indicators, spirit levels, and theodolites for static geometric accuracy measurement. Measurement data processing relies primarily on manual recording and simple interpretation without forming a systematic accuracy database. This mode meets basic needs when equipment accuracy grades are low and production line automation is limited. However, as manufacturing precision requirements reach the micron level, traditional means fall short in measurement sensitivity, data reliability, and installation consistency. The process parameters and operational experience accumulated during installation remain implicit knowledge held by individual technical experts, lacking standardized presentation and organizational inheritance mechanisms.

2.2 New Technical Requirements for Intelligent Equipment Installation Management

Intelligent automated equipment is characterized by multi-axis linkage and compound machining in its mechanical structure. Its electrical control system highly integrates servo drives, sensor detection, and network communication functions, establishing a tighter connection between equipment operational state and installation quality. Installation accuracy requirements have expanded from single-machine geometric accuracy to relative positional accuracy and motion trajectory accuracy between multi-workstations. In industrial robot installation, base levelness errors amplify several-fold at the cantilever end, causing repeat positioning accuracy to exceed process tolerances. The system joint commissioning phase involves parallel, multi-disciplinary work across mechanical assembly, electrical wiring, pneumatic circuits, and software debugging; a deviation in any single link can cause system operational anomalies. Installation management must conform to equipment informatization requirements, seamlessly connecting process data with factory baseline data and subsequent operation and maintenance (O&M) data to achieve digital management throughout the equipment's entire lifecycle.

2.3 Inherent Logic of Integrating Intelligent Technologies with Installation Management

Intelligent technologies such as the Internet of Things (IoT), big data analytics, and digital twins provide a new avenue to resolve these management challenges. Sensor networks enable real-time sensing and continuous recording of key installation parameters, making up for the temporal resolution deficiencies of traditional sampling and periodic inspections. Data analysis algorithms extract systematic patterns of accuracy deviation from multi-source measurement data, determining the causes of deviations and predicting fault development trends. Digital twin technology displays the equipment installation status in a 3D visual format, allowing managers to view the spatial distribution of installation progress and quality metrics in virtual space. The core logic of introducing these technologies is to transform installation management from vague control based on manual experience into precise control driven by data and supported by models, shifting from passive problem handling to proactive risk prevention.[1]

3. Core Problems Facing Automated Mechanical Equipment Installation Management

3.1 Single Installation Accuracy Control Means and Insufficient Process Capability

Currently, installation accuracy detection still relies primarily on post-installation static geometric accuracy re-checks, with inspection items limited to basic indicators like levelness, perpendicularity, and coaxiality. Once an accuracy deviation is detected, the equipment has already been fixed in position; micron-level structural fine-tuning requires repeatedly loosening/tightening anchor bolts or adjusting shims. This adjustment process lacks quantitative guidance and depends on trial-and-error based on maintenance personnel's experience. Micro-vibrations of the foundation and material thermal expansion/contraction caused by environmental temperature changes during installation have not been incorporated into the accuracy control system. Taking high-precision NC machining center installation as an example, environmental vibrations caused by adjacent operating equipment transmit to the bed of the machine tool being leveled, causing continuous fluctuations in dial indicator readings. Installation personnel struggle to judge whether the equipment has achieved optimal levelness, often terminating adjustments based on an empirical sense of stability. Such insufficient process capability leads to significant fluctuations in equipment installation accuracy across different batches.

3.2 Lagging Installation Process Data Acquisition and Weak Decision Support

Process data generated during installation—including measurement data for each step, environmental parameters, and bolt tightening torque values—is currently recorded manually on paper forms, making data integrity, timeliness, and accuracy difficult to guarantee. Measurement data is saved in isolated spreadsheets without cross-process data linkage or traceability. When accuracy exceeds tolerances during system commissioning, troubleshooters must search through records scattered across various processes, resulting in low efficiency and an inability to identify root causes due to incomplete documentation. On-site installation data analysis mostly involves simple comparisons against accuracy standards, lacking deep mining of accuracy deviation trend information hidden within the data, which fails to provide decision support for optimizing installation process parameters or pre-controlling equipment foundations.

3.3 Inefficient Coordination of Multi-Disciplinary Cross-Operations

Automated equipment installation spans multiple disciplines, including mechanical installation, electrical construction, pipeline connection, and software configuration. Each discipline marks its own installation requirements on design drawings, but the process logic and spatial clearance relationships among disciplines are not systematically reviewed. On-site, after mechanical installers complete the assembly of precision components like main spindles and guide rails, electrical personnel install cable trays and perform wiring nearby; without dustproof protection measures, precision kinematic pairs can be contaminated or accidentally bumped. Cross-disciplinary conflicts usually emerge only during the construction phase, making on-site adjustments costly and delaying overall progress. Furthermore, there is no unified information communication medium across disciplines; drawing changes or process adjustment notices rely on verbal transmission or simple written notes, leading to frequent information omissions and misunderstandings.[2]

3.4 Insufficient Installation Process Traceability and O&M Handover

When equipment installation is complete and handed over to the O&M team, installation process documentation generally consists of simplified inspection reports and operation records, lacking detailed explanations of abnormal issues, adjustment measures, and residual risks encountered during installation. When equipment experiences accuracy degradation or abnormal vibration, O&M personnel find it difficult to distinguish whether the issue stems from latent quality hazards during installation or normal operational wear and tear. Essential baseline data from the installation phase—such as initial anchor bolt pre-tightening force values and original guide rail straightness data—is not archived in a structured format, leaving subsequent accuracy restoration and major overhauls without accurate baseline references. This information gap between installation and O&M allows hidden hazards (which could have been resolved through early intervention) to accumulate over time, shortening the equipment's accuracy retention period and increasing lifecycle maintenance costs.

4. Innovative Paths for Automated Mechanical Equipment Installation Management under the Background of Intelligence

4.1 Digital Measurement Technology and Accuracy Pre-Control System Construction

Digital measurement equipment, represented by laser trackers, articulated arm coordinate measuring machines (CMMs), and vision measurement systems, can replace traditional mechanical measuring tools for 3D spatial measurement at micron-level precision. Using digital measurement systems to measure and model baseline parameters—such as foundation flatness, anchor bolt hole positions, and elevations—allows optimal fitting calculations against the equipment's design installation coordinate system. This generates quantitative schemes for adjusting leveling shims and anchor bolts, replacing trial-and-error adjustments. In industrial robot installation, laser trackers measure the flatness and tilt direction of the robot base mounting surface; the software automatically calculates adjustment amounts for each leveling point to guide installers in precise one-time leveling, significantly reducing installation time. Another layer of the accuracy pre-control system involves incorporating environmental factors into installation decision-making. Installing temperature and vibration sensors on-site ensures the system prompts precision measurement and adjustment only when environmental conditions meet a preset stability window, preventing false out-of-tolerance readings caused by environmental fluctuations. Measurement data can also be interactively validated with Finite Element Analysis (FEA) simulation models to predict micro-deformation trends of the equipment base under load in advance, providing references for setting pre-deformation compensation measures. After accumulating installation data from multiple similar units, the system forms an accuracy adjustment case library; when a new installation exhibits similar deviation patterns, the system automatically matches the historical optimal adjustment scheme, reducing trial-and-error time.[3]

4.2 Real-Time Data Acquisition and Intelligent Early Warning Mechanism for Installation

An online data acquisition network covering the entire equipment installation process should be established, with displacement, tilt, and force sensors deployed at key measuring points to display and record leveling/alignment data in real time. Smart torque wrenches are used during bolt tightening; torque-angle curves are uploaded to the management system in real time, where the system automatically verifies whether the tightening process meets specifications and flags abnormal points. Acquisition terminals converge multi-source data into the installation management platform, where built-in data analysis algorithms perform time-series trend analysis on measurement data to identify systematic drift tendencies in accuracy metrics. The early warning module sets pre-warning thresholds and alarm rules for key parameters in each process. If main spindle levelness deviation shows a monotonic increase across several consecutive measurements approaching the upper tolerance limit, the system issues an early warning, prompting installation personnel to pause the current process and investigate, achieving a shift from post-inspection to process prevention. Accumulated process data can also build correlation models between installation quality and operational performance, using big data analysis to identify key installation steps that most impact final operational precision, thereby guiding resource allocation optimization for future projects. Concurrently, when issuing an alarm, the intelligent early warning system automatically generates troubleshooting guidelines listing the most common causes and remedies for similar anomalies in past projects, helping field personnel locate issues quickly.

4.3 Multi-Disciplinary Collaborative Management Platform and Construction Simulation Application

Centering on Building Information Modeling (BIM) technology, a multi-disciplinary collaborative management platform should be established to integrate 3D digital models of mechanical equipment, civil foundations, electrical cable trays, and pipeline layouts into a unified information environment for virtual pre-assembly prior to installation. The platform conducts collision checks and spatial analyses on equipment transport routes, hoisting spaces, and integrated pipeline layouts before construction, identifying and resolving conflicts in advance. During construction, the platform provides a unified process schedule view across disciplines, displaying mechanical, electrical, and pneumatic installation tasks along a timeline while highlighting procedural dependencies and cross-operation zones. When a process in one discipline is delayed or modified, the platform automatically alerts affected tasks in other disciplines. On-site personnel use mobile terminals to view installation guidelines and upload completion statuses and measured data in a timely manner, enabling management to grasp workface progress in real time and creating an information closed loop between the field and management. The platform automatically logs inter-disciplinary conflicts and solutions from each project to form a conflict case library; when similar pipeline crossings or spatial interferences arise in new projects, historical cases are automatically pushed for reference to avoid repeating errors. Using Virtual Reality (VR) technology, managers can intuitively evaluate whether equipment layouts are reasonable through immersive walkthroughs before construction, thereby optimizing operation channels and maintenance space design.[4]

4.4 Lifecycle Quality Traceability and Digital Twin O&M Integration

An installation quality archive should be established with individual equipment as the smallest management unit. Geometric measurement data, key process operation records, abnormal event resolution logs, and historical environmental parameter data from the installation phase are stored in a structured format within a unified equipment information model. Upon installation completion, this model is transferred as a whole to the O&M management system, forming a data continuum from installation to operation. Digital twins built on this model can retrieve baseline accuracy data from the installation phase at any time during O&M to serve as a reference benchmark for current accuracy measurements, assisting in evaluating accuracy degradation amounts and rates. If abnormal vibration increases occur during operation, the digital twin model traces back anchor bolt tightening data and foundation levelness data from the installation phase to determine whether the issue is caused by reduced bolt clamping force or foundation settlement changes over time. Lifecycle quality traceability breaks down information barriers between installation and O&M, transforming equipment management from segmented control to holistic optimization. Based on installation baseline data and real-time operating parameters, digital twins can perform accuracy degradation trend predictions, automatically issuing maintenance recommendations and spare parts demand plans before accuracy degrades to critical thresholds, achieving a transition from preventive maintenance to predictive maintenance. In the event of an unexpected fault, the model rapidly traces all key operation records from the installation phase, helping identify long-term cumulative effects of latent installation quality issues.

5. Safeguard Conditions and Long-Term Development for Innovative Path Implementation

5.1 Installation Management Standardization and Knowledge System Construction

The aforementioned digital measurement methods, data acquisition specifications, and collaborative management workflows should be codified into enterprise-level installation management technical standards and operating procedures (SOPs). A knowledge base of installation processes for typical automated equipment should be created, systematically organizing optimal installation parameters, common accuracy deviation patterns, and adjustment strategies across different machinery types and application scenarios into searchable, reusable knowledge assets. New anomaly cases and solutions emerging from installation sites should be collected regularly to update the knowledge base, converting implicit experience into explicit knowledge, supporting the rapid growth of new personnel, and ensuring consistent installation quality. The knowledge base should employ a hierarchical and classified structure, establishing multi-level indices across dimensions such as equipment type, accuracy grade, fault mode, and solution, enabling field installers to quickly search relevant cases via mobile terminals. Installation technicians should be encouraged to submit long-accumulated operational tips in text, image, or short-video formats; after technical review, these are formally ingested into the library with contributor attribution, forming a positive incentive for knowledge sharing. Operating procedures should dynamically link to the knowledge base so that whenever an installation parameter is updated due to technical improvements, associated SOPs automatically trigger revision workflows, ensuring field execution standards remain synchronized with technological advancements.

5.2 Cultivation of Intelligent Technical Capabilities in Installation Teams

Installation personnel should be organized to systematically study digital measuring instrument operation and measurement error analysis theories, helping them understand measurement principles and application conditions of various digital tools, as well as master measurement data interpretation and processing skills. Practical training on using multi-disciplinary collaborative management platforms should be conducted, covering 3D model browsing, construction progress coordination, and data collection terminal usage. A skill-grading certification system should be established to incorporate digital installation skills into job performance assessments, encouraging installation personnel to proactively adapt to technological changes. The training system must emphasize integrating theory with practical operation by setting up dedicated fault simulation modules where typical installation deviation scenarios are preset on training platforms, requiring trainees to diagnose and adjust using digital tools to hone emergency response capabilities under real working conditions. Mentorship programs ("the experienced leading the new") should be instituted, selecting key technicians with rich digital installation experience to serve as internal trainers who periodically organize field demonstrations and experience-sharing sessions, turning technical inheritance from one-way lectures into interactive seminars. Skill certification should be structured into primary, intermediate, and advanced levels—each corresponding to specific equipment types, accuracy grade requirements, and independent operation authorizations—with certification results tied to compensation and job levels, offering clear career development pathways for installation personnel.[5]

5.3 Investment in Intelligent Installation Equipment and Information Platforms

Enterprises should incorporate digital measurement systems, smart torque tools, and installation management information platform construction into capital expenditure (CapEx) budgets, formulating phased implementation plans. Priority should be given to deploying digital equipment in critical processes with the highest accuracy requirements and quality risks, gradually expanding implementation after accumulating application experience. Platform construction must focus on developing data interfaces with existing equipment management systems and Manufacturing Execution Systems (MES) to prevent new data silos. Attention should be paid to the standardization and localization of relevant technical equipment; under the premise of meeting technical specifications, mature products with strong compatibility and low maintenance costs should be prioritized. During phased implementation, a typical production line or new workshop can be selected as a pilot project to fully record application data of digital equipment and platforms, conducting quantitative comparisons against traditional modes regarding installation efficiency, first-time pass rates, and later fault rates, thereby using objective data to validate return on investment (ROI) and inform subsequent rollout decisions. Platform selection should reserve functional expansion interfaces, accommodating future data exchange needs with external platforms, such as equipment suppliers' remote diagnostic systems and customer factories' MES. Concurrently, periodic calibration and maintenance protocols for smart equipment must be established, supported by dedicated or part-time equipment administrators, to guarantee accuracy, reliability, and long-term availability of digital measurement systems and smart tools, preventing installation quality misjudgments caused by equipment drift.

6. Conclusion

Under the background of intelligence, the innovative transformation of automated mechanical equipment installation management centers on systematically integrating digital measurement, real-time data acquisition, multi-disciplinary collaboration, and lifecycle traceability into traditional installation workflows. Based on analyzing existing issues in installation accuracy control, data-driven decision-making, multi-disciplinary coordination, and process traceability, this paper proposes an innovative path framework spanning accuracy pre-control, process early warning, platform collaboration, and quality traceability. As intelligent sensing technology undergoes further miniaturization and cost reduction, and as digital twin model accuracy improves, automated equipment installation management will move toward higher degrees of digitization and intelligence. Corresponding technical standards and talent cultivation systems should be developed and refined in step with these advances.

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