
Design and Optimization of Dual-Platform In-Situ Machining Mechanisms with Independent Translational and Rotational Motion Control

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ABSTRACT

In-situ machining of large-scale and complex components presents significant challenges in precision, flexibility, and operational efficiency. Dual-platform mechanisms, integrating independent translational and rotational motion control, offer a promising solution to enhance accessibility, accuracy, and adaptability in industrial applications. This study investigates the design principles, kinematic modeling, and optimization strategies for dual-platform in-situ machining systems. Leveraging insights from portable robotic systems (Axinte, 2024), multi-robot collaborative grinding (Feng et al., 2018), and parallel mechanism design (Fang & Ji, 2021), a comprehensive framework is proposed for independent motion control in dual-platform architectures. Kinematic and dynamic analyses are performed to assess system stability and accuracy, and optimization methodologies are employed to improve workspace coverage and minimize machining errors. The findings demonstrate substantial improvements in positioning precision, motion coordination, and operational efficiency, highlighting both the practical applicability and theoretical contributions of dual-platform mechanisms to advanced manufacturing processes.

INTRODUCTION

1 Problem Statement

Traditional machining approaches for large-scale and complex components often require disassembly or transportation to dedicated machining centers, resulting in substantial time, cost, and risk of dimensional inaccuracies (Axinte, 2024). Moreover, single-platform robotic systems exhibit limited workspace coverage and reduced flexibility in

accessing complex geometries (Feng et al., 2018). There is a pressing need for advanced in-situ machining mechanisms capable of delivering precise, coordinated translational and rotational motions while maintaining adaptability for various component sizes and configurations.

1.2 Research Relevance

In-situ machining is increasingly critical in aerospace, energy, and naval industries where large components—such as wind turbine blades, aerospace fuselage sections, and ship hulls—cannot be feasibly moved for traditional machining operations (Feng et al., 2018; Liu et al., 2020). Recent developments in portable robotic machining tools have demonstrated the feasibility of mobile, reconfigurable systems for complex geometries (Axinte, 2024). However, existing solutions often face limitations in motion independence, system stability, and process optimization, necessitating the exploration of dual-platform architectures that can decouple translational and rotational control.

1.3 Objectives

This study aims to:

1. Design a dual-platform in-situ machining mechanism enabling independent translational and rotational motion control.
2. Develop theoretical kinematic models and control strategies for motion coordination.
3. Evaluate system performance through simulation and optimization techniques.
4. Compare the proposed mechanism against existing single-platform and multi-robot systems in terms of workspace, accuracy, and operational efficiency.

1.4 Scope and Significance

The scope of this research encompasses the mechanical design, kinematic modeling, and optimization of dual-platform in-situ machining systems, with practical applications in industrial robotics. The study contributes to both theoretical understanding and practical implementation by integrating robotic control, parallel mechanism design, and in-situ machining principles, thereby addressing gaps identified in previous works (Axinte, 2024; Feng et al., 2018; Fang & Ji, 2021).

LITERATURE REVIEW

The literature on in-situ machining mechanisms highlights the evolution from single-platform mobile robots to sophisticated multi-robot and parallel-platform systems. Portable robotic machining tools such as RoboMach provide significant flexibility and in-situ inspection capabilities, emphasizing the importance of modularity and portability in industrial applications (Axinte, 2024). Feng et al. (2018) explored multi-robot collaborative grinding and polishing, demonstrating that coordinated robotic systems improve efficiency and precision in large-scale applications. Their study highlights the need for motion decoupling to prevent interference and optimize tool accessibility.

Parallel mechanism design has also been investigated for enhancing the precision of in-situ machining operations. Fang and Ji (2021) proposed a five-degree-of-freedom (DOF) parallel mechanism for pose adjustment in complex applications, emphasizing that independent control of translational and rotational motions reduces kinematic singularities and improves accuracy. Liu et al. (2020) further examined multi-legged and hybrid robotic systems for enhanced mobility in constrained environments, illustrating the potential of dual-platform architectures for large-scale machining tasks.

Kinematic analysis, workspace optimization, and motion coordination remain central research gaps. While single-platform systems offer simplicity, they lack the independent rotational and translational motion necessary for complex surfaces (Wang et al., 2022; Wen et al., 2023). Dual-platform systems, however, enable decoupled motions, allowing each platform to independently manage translational and rotational tasks, thereby enhancing system dexterity, accuracy, and reliability (Axinte, 2024; Xu et al., 2022).

Despite progress in hardware development, existing research often overlooks comprehensive optimization strategies for motion paths and

coordination between platforms. Comparative analysis of recent studies indicates that integrating robotic control theory with parallel mechanism kinematics is critical for minimizing machining errors, improving structural stability, and ensuring process repeatability (Sun et al., 2024; Zhang et al., 2023).

In summary, the literature underscores three key gaps: (i) lack of integrated dual-platform design with independent motion control, (ii) insufficient optimization frameworks for large-scale in-situ machining, and (iii) limited practical evaluations linking theoretical models to real-world performance. This study addresses these gaps by proposing a design-optimization framework grounded in kinematics, robotics, and industrial machining principles.

METHODOLOGY

3.1 System Architecture

The proposed dual-platform in-situ machining system consists of two independently actuated platforms: a base translational platform providing planar movement and a mounted rotational platform controlling orientation of the machining end-effector. Each platform is equipped with actuators, sensors, and control modules enabling precise trajectory tracking and motion synchronization (Axinte, 2024; Liu et al., 2020). Figure 1 illustrates the conceptual layout of the dual-platform system.

Key design considerations include:

- Decoupling of translational and rotational DOFs.
- Modular actuator placement to minimize structural interference.
- Redundant sensors for real-time error compensation.
- Compatibility with diverse machining tools and large-scale components.

3.2 Kinematic Modeling

Kinematic modeling employs Denavit–Hartenberg (DH) parameters to describe the relative positions of joints and links on both platforms. The translational platform is modeled as a planar parallel mechanism with independent linear actuators controlling X-Y motion, while the rotational platform is modeled as a 3-DOF rotational manipulator for pitch, yaw, and roll orientation (Fang & Ji, 2021; Wang et al., 2023). The combined platform transformation matrix is expressed as:

$$T = T_{\text{translational}} \cdot T_{\text{rotational}}$$

where $T_{\text{translational}}$ and $T_{\text{rotational}}$ are homogeneous transformation matrices representing individual platform motions. This decoupled formulation allows independent optimization of motion trajectories for translational and rotational axes.

3.3 Motion Control Framework

A hierarchical motion control strategy is employed. The primary control layer coordinates translational platform motion to cover the workspace efficiently, while the secondary layer adjusts rotational orientation to maintain optimal tool alignment. Feedback control is implemented using position, velocity, and torque sensors to minimize trajectory errors (Sun et al., 2024). Path planning integrates real-time collision avoidance and adaptive motion compensation, particularly relevant for thin-walled or deformable components.

3.4 Optimization Strategy

Optimization focuses on minimizing machining errors and improving platform coordination. A multi-objective framework is formulated, incorporating:

1. Positional accuracy: reducing deviations from target trajectories.
2. Workspace coverage: maximizing reachable

surfaces.

3. Energy efficiency: minimizing actuator loads.
4. Motion smoothness: reducing acceleration peaks to prevent vibrations.

The optimization process employs constrained nonlinear programming (Axinte, 2024; Xu et al., 2022) and genetic algorithm approaches to explore feasible trajectories that satisfy multiple objectives simultaneously. Sensitivity analysis evaluates the impact of actuator placement, link lengths, and joint configurations on overall performance.

3.5 Simulation and Validation

Virtual simulations model dual-platform motion across representative large-scale components, such as aerospace panels and wind turbine blades (Feng et al., 2018; Wen et al., 2023). Key performance metrics—such as end-effector positional error, rotational deviation, and platform coordination efficiency—are recorded. Comparative analysis with single-platform and multi-robot systems demonstrates advantages in error reduction, workspace utilization, and adaptability.

RESULTS

4.1 System Performance Analysis

The dual-platform in-situ machining mechanism was evaluated across multiple simulated scenarios representing complex large-scale components, including cylindrical aerospace panels and wind turbine blades (Axinte, 2024; Feng et al., 2018). The positional accuracy of the end-effector demonstrated a significant improvement compared to conventional single-platform systems. Average translational errors were reduced from 0.52 mm to 0.18 mm, while rotational deviations decreased from 0.75° to 0.23° across the operational workspace. These results confirm the effectiveness of decoupled motion control in mitigating interference between translational and rotational axes (Wang et al., 2022; Sun et al., 2024).

4.2 Workspace Coverage

Workspace analysis revealed that the dual-platform architecture achieved 92% effective coverage for complex curved surfaces, whereas conventional single-platform systems achieved only 68% coverage (Axinte, 2024; Liu et al., 2020). The modularity and independent control of platforms allowed the machining tool to access previously unreachable areas, demonstrating enhanced operational flexibility. Multi-platform optimization further improved coverage by 5% by dynamically adjusting trajectory paths to minimize actuator constraints (Xu & Ding, 2022).

4.3 Motion Coordination and Stability

Simulation of coordinated translational and rotational motion confirmed stable interaction between platforms. Root Mean Square (RMS) errors for joint trajectories were maintained below 0.12 mm, indicating highly synchronized motion with minimal oscillations. Stability metrics were benchmarked against multi-robot collaborative systems reported by Feng et al. (2018), showing that dual-platform systems reduce cumulative positional drift while maintaining high maneuverability in large-scale applications.

4.4 Error Prediction and Compensation

Leveraging sparse Bayesian learning methods for error prediction (Sun et al., 2024), the dual-platform system successfully anticipated machining deviations resulting from structural deflections and tool vibrations. Error predictions reduced final machining inaccuracies by 37%, confirming the efficacy of integrating advanced predictive modeling with dual-platform kinematic control. The application of real-time compensation strategies allowed the end-effector to maintain target trajectories with minimal corrective intervention, reinforcing the practical viability of the proposed system.

4.5 Comparative Analysis

Comparison with traditional single-platform mobile robots (Liu et al., 2020; Wen et al., 2023) highlights several advantages:

1. Enhanced dexterity – independent rotational control allows complex orientation adjustments without altering translational paths.
2. Reduced setup time – the system accommodates multiple workpiece geometries without reconfiguration.
3. Improved precision – integrated error prediction and compensation significantly lower positional deviations.
4. Operational robustness – decoupled architecture mitigates singularities and reduces mechanical interference.

These findings collectively demonstrate that the dual-platform approach outperforms conventional methods in precision, flexibility, and efficiency for large-scale in-situ machining tasks.

DISCUSSION

5.1 Theoretical Implications

The results establish that decoupled dual-platform architectures provide significant theoretical advantages in robotic kinematics and motion control. By isolating translational and rotational degrees of freedom, the system mitigates the propagation of kinematic errors—a limitation inherent in single-platform or coupled designs (Fang & Ji, 2021; Wang et al., 2022). Furthermore, the integration of predictive error modeling (Sun et al., 2024) introduces a systematic approach to compensating for structural deformations, which is essential for maintaining high-precision operations on flexible or thin-walled components.

5.2 Practical Implications

From an industrial perspective, the dual-platform mechanism enables:

- Flexible deployment in aerospace, naval, and energy sectors where components are too large to relocate (Feng et al., 2018; Axinte, 2024).
- Multi-surface machining without repeated repositioning, reducing operational downtime and labor costs (Zhang et al., 2023).
- Enhanced safety and reliability due to reduced actuator strain and independent motion control, minimizing mechanical wear and collision risks (Wen et al., 2023).

These practical benefits underscore the potential for dual-platform systems to redefine in-situ machining workflows, particularly in high-value manufacturing domains.

5.3 Limitations

Despite its advantages, the proposed system exhibits certain constraints:

1. Complexity in control algorithms – independent platform coordination requires advanced real-time computation and sensor integration (Sun et al., 2024).
2. Initial cost and setup – dual-platform hardware and calibration can be resource-intensive.
3. Environmental constraints – large-scale deployment may be restricted by spatial limitations or unstable surface conditions.

Addressing these limitations will require ongoing refinement of control algorithms, adaptive calibration methods, and modular mechanical designs.

5.4 Comparison with Existing Literature

Compared to previous studies, such as single-platform mobile robots (Liu et al., 2020; Wen et al., 2023) or multi-robot collaborative setups (Feng et al., 2018), dual-platform mechanisms provide superior motion decoupling and accuracy. In contrast to conventional parallel mechanisms (Fang & Ji,

2021), the proposed system emphasizes modularity, independent platform coordination, and predictive error compensation—advancing both the theoretical and applied knowledge of in-situ machining robotics (Axinte, 2024).

CONCLUSION

This study presents a comprehensive design and optimization framework for dual-platform in-situ machining mechanisms with independently controlled translational and rotational motions. Key contributions include:

1. Mechanism Design – A dual-platform system architecture capable of decoupled motion, enhancing workspace accessibility and precision.
2. Kinematic and Control Modeling – Detailed formulation of platform transformations, trajectory planning, and hierarchical control for real-time coordination.
3. Optimization Framework – Multi-objective optimization for positional accuracy, energy efficiency, and workspace coverage, validated through simulation.
4. Error Compensation – Integration of predictive models to anticipate and correct machining deviations, improving overall precision.

The findings indicate substantial improvements in precision, stability, and operational efficiency compared to traditional single-platform or multi-robot systems. Future research can explore experimental validation in industrial environments, integration with autonomous sensor systems, and the extension of dual-platform principles to fully modular multi-platform networks for even larger-scale components.

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