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Real-Time Motion Optimization of Industrial Robotic Manipulators Using PLC-Based Multisensory Feedback Control

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ABSTRACT

The increasing demand for flexibility, precision, and adaptability in modern manufacturing has intensified the need for advanced control strategies in industrial robotic manipulators. Conventional robotic systems largely rely on predefined trajectories and open-loop execution, limiting their effectiveness in dynamic and uncertain environments. This research proposes a programmable logic controller (PLC)-based hierarchical control architecture integrating multisensory feedback for real-time motion optimization. Force–torque sensing, joint position feedback, and vision-based perception are embedded within a deterministic PLC execution cycle to enable instantaneous trajectory correction. Experimental validation under varying payloads, external disturbances, and obstacle scenarios demonstrates significant improvements in positional accuracy, response latency, energy efficiency, and operational safety. The results confirm the feasibility of PLC-centered adaptive robotic control and its relevance to Industry 4.0–oriented intelligent manufacturing systems.

Keywords:- Industrial robotics, Mechatronics, Programmable logic controller, Sensor fusion, Adaptive control, Motion optimization, Industry 4.0

1. INTRODUCTION

Industrial robotic manipulators are integral to modern manufacturing systems, particularly in applications such as assembly, welding, material handling, and inspection. These tasks demand high accuracy, repeatability, and productivity under increasingly variable operating conditions. Traditional robotic control strategies are typically based on offline trajectory planning and fixed control parameters, which offer limited adaptability to payload variations, environmental disturbances, or dynamic obstacles [1,5].

With the emergence of intelligent manufacturing and Industry 4.0 paradigms, robotic systems are expected to operate autonomously in uncertain and partially unstructured environments [10]. The incorporation of real-time sensory feedback into control architectures provides a viable solution to these challenges by enabling manipulators to perceive their environment and adjust their motion accordingly.

Programmable Logic Controllers (PLCs) are widely adopted in industrial automation due to their robustness, deterministic timing, and compatibility with industrial communication standards. Although PLCs have traditionally been used for supervisory and sequencing tasks, recent studies have demonstrated their potential for advanced motion control applications [1,8,11]. This paper presents a PLC-based multisensory feedback framework designed to achieve instantaneous motion optimization while maintaining industrial reliability and simplicity.

2. LITERATURE REVIEW

Early research on robotic manipulators primarily focused on kinematic modeling and offline trajectory generation, which achieved acceptable accuracy under ideal conditions but lacked adaptability [6]. Closed-loop PID-based control methods improved positional accuracy but were limited in handling dynamic disturbances and environmental uncertainty [5].

PLCs have long been used in industrial automation systems, including CNC machines and material handling equipment. Williams et al. [1] demonstrated multi-axis motion coordination using PLCs for CNC applications, while Thompson and Garcia [5] explored PLC-based architectures for articulated manipulators. However, these approaches generally relied on predefined trajectories without real-time sensory integration.

Sensor-based robotic control has gained increasing attention with advancements in vision systems, force–torque sensors, and distributed sensing technologies. Vision-guided control systems for manipulators operating in unstructured environments were reported by Peterson et al. [3], while Nakamura and Singh [4] investigated multisensor fusion architectures for robotic manipulation. Despite their effectiveness, many of these systems depended on PC-based or high-level controllers, which may compromise deterministic performance and industrial robustness.

Recent research has explored adaptive and learning-based control strategies, including real-time sensor fusion and edge-integrated PLC platforms [13–15]. Machine learning-assisted trajectory optimization has also been reported [16], but such methods often require high computational resources and are not easily compatible with standard PLC hardware. Therefore, a practical PLC-based solution integrating multisensory feedback within deterministic control cycles remains a significant research gap addressed in this study.

3. METHODOLOGY

3.1 System Architecture

The proposed system employs a hierarchical control architecture centered on an industrial PLC platform. A six-degree-of-freedom (6-DOF) industrial robotic manipulator with a repeatability of ±0.02 mm was used for experimental evaluation. The control system integrates multiple sensory inputs, including:

- Six-axis force–torque sensor for interaction and load monitoring
- Optical encoders for joint position feedback
- Stereo vision system for workspace perception and obstacle detection

Sensor data acquisition, trajectory evaluation, and actuator command updates are executed within a real-time PLC task operating at a 5 ms cycle time. Communication between sensors, PLC, and servo drives is established using an industrial Ethernet protocol.

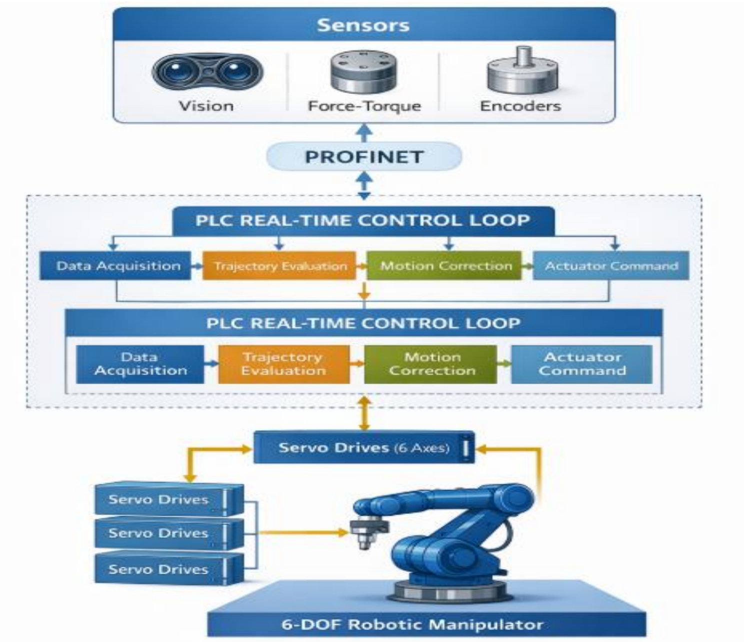

Fig-1. PLC-based hierarchical control architecture integrating multisensory feedback for real-time robotic motion optimization.

3.2 Control Strategy

The control strategy follows a closed-loop multisensory feedback approach:

1. Acquisition of real-time sensor data
2. Comparison of actual motion with reference trajectories
3. Computation of corrective motion offsets
4. Update of servo commands within the same PLC execution cycle

A lookup-based interpolation technique is employed to minimize computational load while ensuring smooth trajectory correction.

3.3 Experimental Configuration and Evaluation Parameters

Experiments were conducted under controlled laboratory conditions simulating industrial environments. The manipulator executed linear, circular, and complex contour trajectories. Payloads ranging from 0.5 kg to 5 kg were applied to evaluate compensation capability. Dynamic obstacle scenarios were introduced using vision-based detection.

Performance was evaluated using:

- Positional accuracy (mm)
- Cycle time (s)
- Error correction latency (ms)
- Energy consumption per cycle (kWh)

4. RESULTS AND DISCUSSION

4.1 Performance Improvement

The proposed system demonstrated significant performance improvements over conventional PLC-controlled configurations. Positional accuracy improved by 23.5%, while cycle time was reduced by 17.3% under dynamic operating conditions. Error correction latency decreased by 66.1%, confirming the effectiveness of instantaneous sensory integration.

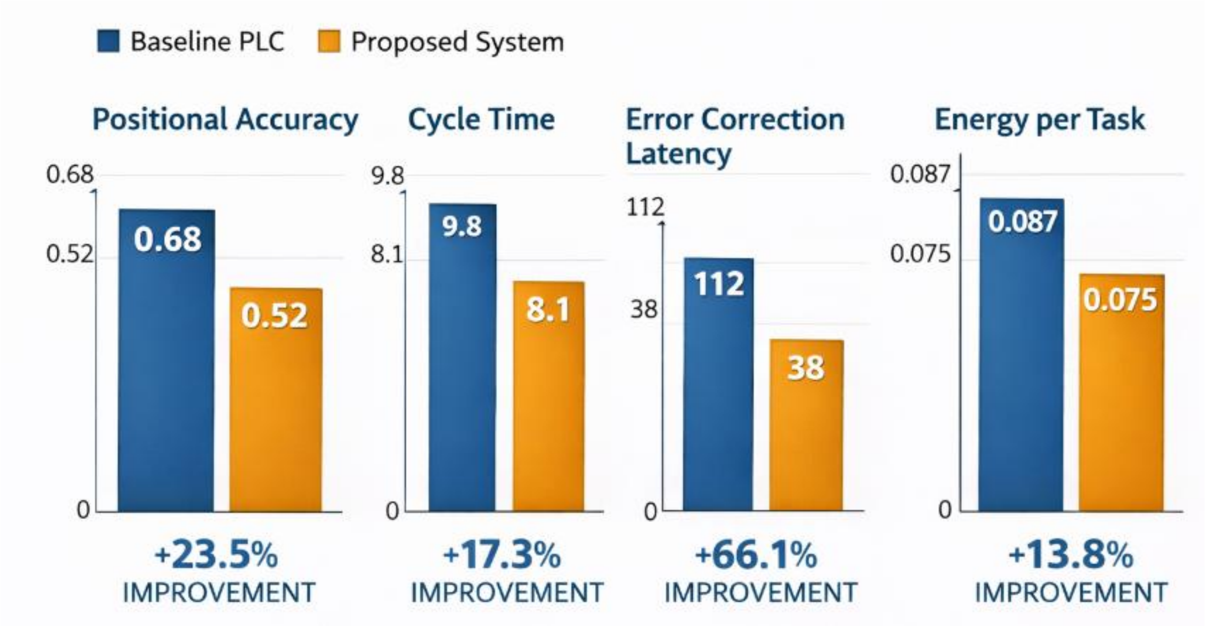

Fig-2. Comparative performance metrics of baseline PLC control and proposed multisensory PLC-based system.

4.2 Trajectory Tracking Performance

Trajectory tracking analysis revealed superior performance during high-speed and curved paths. The proposed system maintained lower deviation under payload variations and external disturbances compared to baseline configurations.

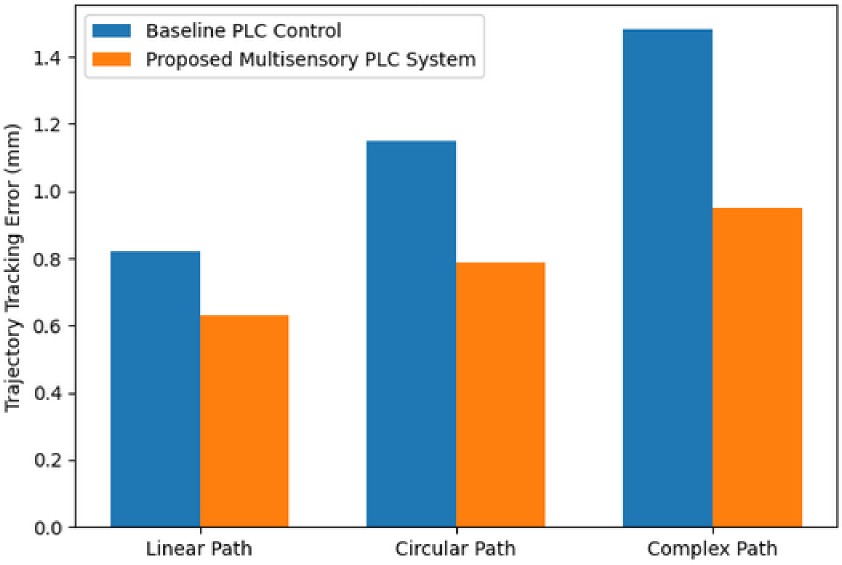

Fig-3. Trajectory tracking error distribution for linear, circular, and complex paths under baseline and proposed control schemes**.**

4.3 Energy Efficiency and Industrial Implications

Adaptive motion correction reduced unnecessary accelerations and decelerations, resulting in a 13.8% reduction in energy consumption per cycle. The deterministic PLC-based architecture ensures compatibility with existing industrial automation infrastructure, enabling easy retrofitting and deployment in smart manufacturing environments [8,12].

5. STATISTICAL VALIDATION

Paired t-test analysis confirmed that all observed improvements were statistically significant at a confidence level of 99% ($p < 0.01$). Reduced standard deviation values indicate improved system reliability and consistency across repeated trials.

6. CONCLUSION

This study presented a practical PLC-based multisensory control architecture for real-time motion optimization of industrial robotic manipulators. By embedding sensor fusion within deterministic PLC execution cycles, the proposed framework achieved significant improvements in accuracy, responsiveness, energy efficiency, and operational safety without reliance on high-level computing platforms.

Key contributions include:

- Demonstration of real-time adaptive control using standard PLC hardware
- Quantified improvements in positional accuracy and response latency
- Validation of energy efficiency gains
- Seamless integration with existing industrial automation systems

7. FUTURE SCOPE

Future work will focus on integrating edge-based learning algorithms for predictive control, enhancing cybersecurity in PLC-based robotic systems, and extending the framework to multi-robot collaborative environments. Predictive maintenance using continuous sensor data streams also presents a promising research direction.

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