

Theoretical Modeling and Compensation of Errors in Industrial Robot Accuracy and Repeatability

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Abstract

Industrial robots are integral to modern manufacturing systems, enabling high precision, high throughput, and flexibility. However, errors in accuracy and repeatability, which arise from a variety of sources such as mechanical wear, calibration issues, and environmental factors, can significantly impact the performance of industrial robots. This paper aims to explore the theoretical modeling of errors in industrial robot systems and propose compensation strategies to enhance their accuracy and repeatability. Key factors contributing to errors, such as kinematic, dynamic, and environmental influences, are discussed in detail. Additionally, the paper explores various compensation techniques, including geometric error compensation, dynamic compensation, and adaptive control approaches. Through the integration of error modeling and compensation methods, industrial robots can achieve improved performance, ensuring higher operational efficiency and product quality. The paper concludes by highlighting the challenges and future research directions for improving the accuracy and repeatability of industrial robots in practical applications.

Keywords: *Industrial Robots; Accuracy; Repeatability; Error Modeling; Compensation Strategies; Kinematic Errors; Dynamic Errors; Adaptive Control*

1 INTRODUCTION

In modern manufacturing systems, industrial robots play a critical role in improving efficiency, precision, and flexibility. However, the accuracy and repeatability of industrial robots remain significant concerns that affect their performance. While these robots are designed to operate with high precision, several factors such as mechanical wear, sensor inaccuracies, and environmental disturbances can introduce errors. These errors can cause deviations in robot motion, resulting in misalignment, misplacement of objects, and suboptimal product quality. Therefore, addressing the issues of robot accuracy and repeatability is essential for enhancing the overall performance and reliability of robotic systems in industrial settings. The motivation for this research lies in the need to improve industrial robot performance through error modeling and compensation strategies. By understanding the sources of errors and applying advanced compensation techniques, the accuracy and repeatability of robots can be significantly enhanced. This paper provides a theoretical framework for error modeling and explores compensation methods that can mitigate the effects of these errors in real-time.

2 SOURCES OF ERRORS IN INDUSTRIAL ROBOTS

2.1 Kinematic Errors

Kinematic errors in industrial robots arise from inaccuracies in the robot's geometric configuration, such as link lengths, joint angles, and other mechanical tolerances. These errors are primarily associated with the robot's movement along its degrees of freedom and can be modeled using kinematic equations that describe the robot's motion. Even small deviations in the robot's mechanical components can lead to significant errors in its final position and orientation. Understanding and quantifying these errors is crucial for improving robot accuracy.

2.2 Dynamic Errors

Dynamic errors are caused by the forces and accelerations experienced by the robot during its motion. These errors are a result of the robot's dynamics, including inertial forces, friction, and damping. Dynamic inaccuracies often become more pronounced during high-speed movements or when the robot is carrying heavy loads. These errors can be modeled through dynamic equations that account for the robot's mass, stiffness, and external forces. Identifying and compensating for dynamic errors is essential for improving the repeatability of industrial robots, particularly in high-performance applications^[1].

2.3 Environmental Factors

Environmental factors, such as temperature fluctuations, vibrations, and air pressure, can also influence the accuracy and repeatability of industrial robots. These external disturbances may cause thermal expansion of materials, deformation of robot structures, or changes in sensor readings. Environmental influences are often unpredictable and require careful modeling and compensation to minimize their impact on robot performance. Understanding the interactions between environmental conditions and robotic systems is critical for ensuring reliable and precise operations^[2].

2.4 Sensor and Calibration Errors

The accuracy of industrial robots is also affected by errors in sensors and calibration. Sensors used for position and orientation feedback, such as encoders and cameras, may have inherent inaccuracies due to limitations in resolution, noise, or calibration errors^[3]. Regular calibration and the use of advanced sensor technologies are essential for minimizing these types of errors. Understanding the calibration procedures and the effects of sensor inaccuracies on robotic performance is important for improving the overall system's repeatability and accuracy.

3 THEORETICAL MODELING OF ROBOT ERRORS

3.1 Kinematic Error Modeling

Kinematic error modeling focuses on the geometric errors associated with the robot's movement. It involves the use of transformation matrices and Denavit-Hartenberg (DH) parameters to model the robot's motion. The robot's forward and inverse kinematics are used to calculate the position and orientation of the end effector, and errors can be introduced due to inaccuracies in the robot's link lengths, joint angles, or other mechanical components. The kinematic error model typically includes the analysis of errors in position, orientation, and joint angles^[4].

3.2 Dynamic Error Modeling

Dynamic error modeling involves the use of equations of motion to describe the forces, accelerations, and velocities affecting the robot's joints and links. Dynamic errors are often influenced by inertial forces, damping, and friction. In dynamic error modeling, the robot's mass, stiffness, and the external forces acting on it must be taken into account^[5]. The model can be used to simulate the robot's movement and predict errors in its trajectory due to dynamic effects.

3.3 Environmental Error Modeling

Environmental error modeling requires the consideration of external factors such as temperature, vibration, and humidity that can affect the robot's components. Thermal expansion of materials, changes in the material properties due to temperature variations, and the impact of vibrations can be modeled using thermodynamic and dynamic equations. The effects of environmental factors can be quantified and incorporated into the robot's error model to improve accuracy and repeatability^[6].

4 COMPENSATION TECHNIQUES FOR ROBOT ERRORS

4.1 Geometric Error Compensation

Geometric error compensation aims to correct for inaccuracies in the robot's geometric configuration. This involves

the use of calibration techniques to determine the errors in link lengths, joint angles, and other parameters. Once the errors are identified, compensation algorithms are implemented to adjust the robot's trajectory, ensuring that the end effector reaches the desired position with high accuracy. Techniques such as least-squares optimization, machine learning, and closed-loop feedback are commonly used for geometric error compensation.

4.2 Dynamic Error Compensation

Dynamic error compensation involves adjusting the robot's control inputs to account for inertial forces, friction, and other dynamic effects. This can be achieved through advanced control algorithms, such as model-based control, that predict the robot's dynamic behavior and adjust its movement accordingly. Additionally, force and torque sensors can be integrated into the robot to provide real-time feedback, enabling dynamic compensation during high-speed or high-load operations^[7].

4.3 Adaptive Control for Error Compensation

Adaptive control techniques are used to adjust the robot's control parameters in real time based on observed performance. These methods enable the robot to compensate for errors that arise during operation, particularly those caused by changes in the robot's environment or operational conditions. Adaptive control algorithms use feedback loops to continuously adjust the robot's motion, ensuring that it maintains high accuracy and repeatability even in the presence of varying disturbances.

4.4 Hybrid Error Compensation Approaches

Hybrid error compensation combines multiple compensation strategies to address the different types of errors that affect robot performance. For example, a hybrid system might combine geometric error compensation with dynamic error compensation to address both mechanical inaccuracies and dynamic effects^[8]. Machine learning techniques can also be integrated into hybrid systems to improve the accuracy of error predictions and compensations over time.

5 CONCLUSION

The accuracy and repeatability of industrial robots are critical factors that influence their performance and effectiveness in manufacturing operations. Errors in robot motion arise from various sources, including kinematic, dynamic, and environmental factors, as well as sensor inaccuracies and calibration issues. Theoretical modeling of these errors provides valuable insights into their impact on robotic performance, enabling the development of effective compensation strategies.

Compensation techniques such as geometric error compensation, dynamic error compensation, and adaptive control can significantly improve robot accuracy and repeatability, ensuring higher operational efficiency and product quality. Despite the progress made in error modeling and compensation, challenges remain in real-world implementation, particularly with respect to the integration of advanced algorithms and the compensation of environmental factors.

Future research should focus on improving the accuracy of error models, exploring new compensation techniques, and integrating machine learning and artificial intelligence to enable real-time adaptation to changing conditions. By overcoming these challenges, the performance of industrial robots can be further enhanced, leading to more efficient and reliable manufacturing systems.

REFERENCES

- [1] Guo X, Zhu B, Chi M, et al. Modeling and compensation of measurement errors in hand-eye system for heavy-load industrial robots with line laser sensor[J].Robotics and Computer-Integrated Manufacturing,2026,98:103155-103155. DOI:10.1016/J.RCIM.2025.103155.
- [2] Woodside R M, Bristow A D, Landers G R .AN IMPROVED KINEMATIC ERROR CONTROLLER FOR REAL-TIME KINEMATIC ERROR COMPENSATION OF INDUSTRIAL ROBOTS[J].Proceedings of the International Symposium on Flexible Automation,2022,331-338.DOI:10.11509/ISFA.2022.331.

- [3] Woodside R M, Cui T, Emelko J, et al. A feedforward kinematic error controller with an angular positioning deviations model for backlash compensation of industrial robots[J].*Manufacturing Letters*,2024,41(S):1579-1584.
DOI:10.1016/J.MFGLET.2024.09.184.
- [4] Wei W, Wei T, Wenhe L, et al. Error compensation of industrial robot based on deep belief network and error similarity[J].*Robotics and Computer-Integrated Manufacturing*,2022,73.DOI:10.1016/J.RCIM.2021.102220.
- [5] Zhang T, Chen Y, Zou Y .Joint torque estimation method of industrial robot by combining error compensation model based on LSTM and iterative weighted parameter identification[J].*Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*,2025,239(3):373-390.DOI:10.1177/09596518241282097.
- [6] Asif S, Webb P .Managing Delays for Realtime Error Correction and Compensation of an Industrial Robot in an Open Network[J].*Machines*,2023,11(9):863.DOI:10.3390/MACHINES11090863.
- [7] Wang Z, Dong H, Bai S, et al. A new approach of kinematic geometry for error identification and compensation of industrial robots[J].*Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*,2019,233(5):1783-1794.DOI:10.1177/0954406218772595.
- [8] Lou Z, Zhou J, Zhang J, et al. Drilling errors compensation of industrial robot based on 3D passive scale tracker[J].*Measurement Science and Technology*,2024,35(9):DOI:10.1088/1361-6501/AD4E53.