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PRECISION ASSESSMENT AND PREDICTIVE COMPENSATION OF ABB IRB 1600 ROBOT USING C-TRACK 780 OPTICAL TRACKING IN SMART MANUFACTURING

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Abstract: In data-driven manufacturing, external metrology plays a crucial role in ensuring robotic accuracy. This study investigates the positioning accuracy of the ABB IRB 1600-5/1.45 industrial robot using the C-Track 780 optical tracker. Experiments were conducted under varying payloads and motion speeds, and deviations between commanded and actual TCP positions were recorded. A central research question addressed is whether data from C-Track 780 are sufficiently stable and precise to model positioning errors for predictive correction. Results show consistent patterns of deviation influenced by dynamic conditions and validate the use of optical tracking for real-time quality monitoring and error compensation, contributing to improved accuracy in smart manufacturing systems.

Key words: Industrial robotics, Positioning accuracy, Optical tracking system, C-Track 780, Data-driven manufacturing, Error compensation, Smart manufacturing.

1. INTRODUCTION

The advent of Industry 4.0 has introduced a paradigm shift in manufacturing, emphasizing smart, flexible, and highly efficient production systems. At the heart of these systems are industrial robots, whose speed, repeatability, and versatility enable a wide range of automated tasks. Nevertheless, achieving high absolute positioning accuracy remains a persistent challenge, particularly in precision-critical operations such as robotic machining, precision assembly, and human-robot collaboration [1].

While modern robots exhibit outstanding repeatability, their absolute positioning accuracy is often compromised by several factors, including joint compliance, gear backlash, payload-induced deflections, thermal expansion, and dynamic inertial effects [2][3]. These inaccuracies can become critical in manufacturing processes that require micrometer-level tolerances.

Traditional calibration techniques have focused on improving offline robot models, but they frequently fall short when dynamic conditions change during operation [2][4]. Therefore,

integrating external metrology systems into the manufacturing environment has emerged as a vital strategy for real-time monitoring and correction of robot positioning [5].

Among external metrology tools, optical tracking systems stand out for their non-contact operation, high spatial resolution, and adaptability to dynamic environments. In particular, the C-Track 780 optical tracker developed by Creaform has demonstrated robust capabilities for high-precision monitoring of robotic systems in production scenarios.

Despite these technological advances, there remains a crucial need for predictive compensation methods that not only detect but proactively correct robot positioning errors based on operating conditions such as payload and speed. By leveraging data-driven models, it becomes possible to preemptively adjust robot trajectories and enhance absolute accuracy without interrupting the manufacturing workflow.

This study addresses these challenges by:

- Rigorously assessing the absolute positioning accuracy of the ABB IRB 1600-5/1.45 robot using the C-Track 780 optical tracking

system under varying payload and speed conditions.

- Statistically validating the influence of these dynamic factors on positioning errors using two-way Analysis of Variance (ANOVA) [3].
- Developing and proposing a predictive error compensation function that can be integrated into robotic operations to dynamically adjust for systematic deviations.

Through these contributions, the study aims to enhance the precision, adaptability, and reliability of industrial robotic systems operating in smart manufacturing environments.

2. THEORETICAL BACKGROUND

2.1 Accuracy and Repeatability in Robotics

The performance of industrial robots is typically evaluated using two fundamental but distinct concepts: repeatability and accuracy.

Repeatability refers to a robot's ability to return consistently to the same position under identical operating conditions. It is primarily influenced by the mechanical quality of the robot's joints and the precision of its control algorithms. High repeatability, often in the order of a few hundredths of a millimeter, is a hallmark of modern industrial robots and is critical for tasks involving repetitive motion.

Accuracy, on the other hand, measures the deviation between the commanded and the actual end-effector position within the robot's workspace. Accuracy is influenced by multiple factors, including joint compliance, gear backlash, sensor errors, structural deformations, thermal effects, and dynamic operational loads. Unlike repeatability, achieving high accuracy often requires external calibration or real-time error compensation mechanisms.

The ISO 9283 standard provides formal definitions and procedures for measuring robot performance, emphasizing that while high repeatability is common, absolute positioning accuracy typically requires enhancement through calibration or external metrology.

Given that many advanced manufacturing applications demand precise robot-environment interactions, improving absolute positioning accuracy is becoming increasingly critical.

2.2 ABB IRB 1600 Overview

The ABB IRB 1600-5/1.45 is a widely used industrial robot offering a combination of speed, flexibility, and precision, making it suitable for tasks such as machine tending, material handling, assembly, and arc welding. Key specifications include:

- Maximum payload capacity: 5 kg
- Maximum horizontal reach: 1.45 meters
- Nominal repeatability: ± 0.02 mm (ISO 9283 standard)

The robot is equipped with ABB's IRC5 controller, which features advanced motion control algorithms designed to minimize trajectory errors and improve path fidelity. Despite these capabilities, real-world factors such as payload variations, dynamic effects, and mechanical wear can introduce significant deviations in absolute positioning, especially critical in smart manufacturing environments where accuracy is paramount.

External measurement systems thus play a vital role in monitoring and compensating these deviations to maintain the robot's operational reliability and precision.

2.3 Optical Tracking Systems and C-Track 780

Optical tracking systems are increasingly utilized in industrial applications requiring precise, real-time position and orientation measurements. These systems use stereoscopic camera setups to track retroreflective markers, allowing for six degrees of freedom (6-DOF) measurements without physical contact.

The C-Track 780, developed by Creaform, is a portable optical tracker known for:

- Volumetric measurement accuracy up to 0.025 mm
- High acquisition rates suitable for dynamic robotic operations
- Integrated ambient light compensation for stable performance under varying conditions
- Real-time tracking of 6-DOF poses (position and orientation).

In this study, the C-Track 780 was used to monitor the Tool Center Point (TCP) of the ABB IRB 1600 during dynamic trajectories under various payload and speed settings. Its high stability and precision make it an ideal instrument for evaluating and enhancing robotic positioning

performance in real-world manufacturing conditions.

2.4 Statistical Validation using Two-Way ANOVA

Experimental data often contains variability due to multiple operational factors. To rigorously determine whether observed differences in positioning errors are statistically significant, a Two-Way Analysis of Variance (ANOVA) was employed.

The two factors considered were:

- Payload (with three levels: 0 kg, 2 kg, 4.5 kg)
- Motion Speed (with two levels: low speed — 25% nominal, and high speed — 100% nominal).

Two-way ANOVA allows for:

- Assessing the main effect of each factor independently (i.e., how payload alone or speed alone influences positioning errors).
- Evaluating any interaction effect between payload and speed (i.e., whether the combined effect of high payload and high speed significantly alters the error magnitude beyond the sum of individual effects).

This statistical approach provides a robust basis for understanding the impact of operational conditions on robot accuracy and for designing targeted compensation strategies.

2.5 Predictive Error Compensation Strategy

Based on the experimental results and statistical analyses, a predictive error compensation function was developed to proactively adjust the robot's commanded positions.

The compensation function is based on a linear model relating the positioning error (Δ_{error}) to the operational parameters:

$$\Delta_{\text{comp}} = a \times \text{Payload} + b \times \text{Speed} + c$$

where:

- a and b are regression coefficients derived from experimental data,
- c is a bias term accounting for baseline systematic deviations.

By applying this compensation at the trajectory planning level, the robot's absolute positioning errors can be significantly reduced

without altering its internal control architecture. This predictive approach aligns with the principles of smart manufacturing, enabling real-time adaptation to dynamic operating conditions and enhancing overall system robustness.

Recent, Liu et al. [6] proposed an optical-tracking-based calibration method using kinematic parameter identification, achieving sub-millimeter positioning accuracy in real industrial setups. This supports the feasibility of using external metrology not only for monitoring but also for proactive correction of robotic motion in dynamic environments.

3. EXPERIMENTAL METHODOLOGY

3.1 Experimental Setup

The experimental setup was designed to rigorously evaluate the absolute positioning accuracy of the ABB IRB 1600-5/1.45 robot using the C-Track 780 optical tracking system under controlled laboratory conditions.

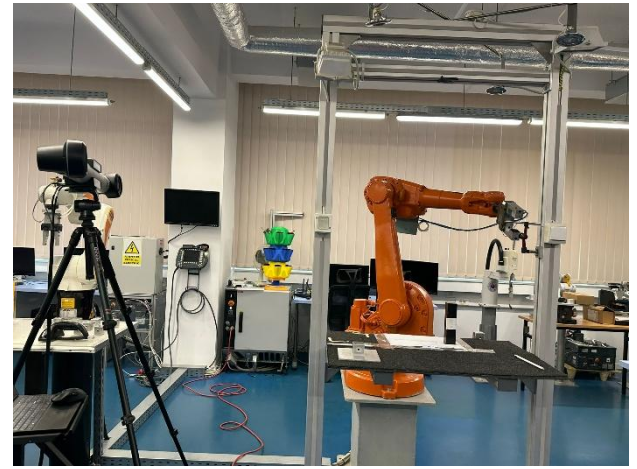


Fig. 1. Experimental setup with ABB IRB 1600 and C-Track 780

The main components of the experimental configuration included:

- The ABB IRB 1600 robot mounted on a rigid steel base to minimize external vibrations and enhance stability.
- The C-Track 780 optical tracker, positioned strategically to cover the full operational workspace of the robot without occlusions or blind spots.
- A rigid marker support frame attached to the Tool Center Point (TCP) of the robot,

equipped with retroreflective markers optimized for optical tracking.

- ABB's IRC5 controller used to program predefined trajectories and execute precise motion sequences.
- A data acquisition system interfaced with the C-Track 780, responsible for real-time capture and storage of TCP position and orientation data.



Fig. 2. Robot gripper (SCHUNK) holding test artifact Ce

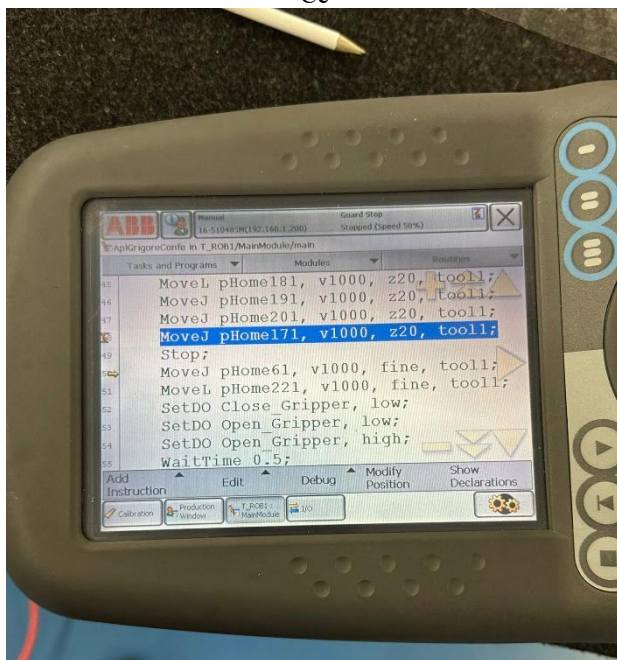


Fig. 3. ABB code used for programming robot trajectories

Environmental conditions, including ambient temperature and lighting, were controlled to minimize measurement noise and ensure the stability of optical tracking. The reference coordinate system was established through the internal calibration routine of the C-Track 780 system, and appropriate transformation matrices were applied to align measurements with the robot's base frame.

The robot's programmed trajectories included linear and point-to-point (PTP) movements across the workspace, simulating typical industrial operations. These trajectories were repeated under varying payload and speed conditions, enabling a comprehensive evaluation of positioning performance.

3.2 Test Procedures

The testing procedures were structured to systematically investigate the influence of payload and motion speed on the absolute positioning accuracy of the robot.

Three payload configurations were tested:

- No payload (only the marker support frame, approximately 0.5 kg),
- Light payload (approximately 2 kg),
- Heavy payload (approximately 4.5 kg).

For each payload, the robot executed two types of motion:

- Low-speed motion (25% of nominal joint speeds),
- High-speed motion (100% of nominal joint speeds).

The robot was commanded to sequentially reach a set of 20 predefined target points distributed throughout its workspace. At each target:

- The robot paused for two seconds to ensure stable data acquisition.
- The C-Track 780 system recorded the TCP position at a sampling rate of 60 Hz.
- Approximately 120 position samples were collected per target point per cycle.

Each trajectory execution, encompassing all 20 target points, was repeated five times for each payload-speed combination to enable statistical evaluation of repeatability and accuracy.

In total, the experimental matrix comprised:

- 3 payload levels $\times$ 2 speed levels $\times$ 5 repetitions = 30 complete test cycles,
- Resulting in data from 600 target acquisitions (20 points $\times$ 30 cycles).

This robust experimental design allowed for both the evaluation of mean errors and the statistical analysis of variability and factor interactions.

3.3 Data Collection and Preparation

The data collected from the C-Track 780 were processed as follows:

- For each static acquisition interval at a target point, the mean TCP position was calculated to minimize sensor noise effects.
- The positioning error vector was determined as the difference between the commanded TCP position and the measured mean position.
- The magnitude of the positioning error (Euclidean norm) was computed for each target point.

Two key performance metrics were extracted:

- Mean Absolute Positioning Error (MAPE): the average magnitude of positioning error across all target points in a test cycle.
- Standard Deviation of TCP Positions: used as an indicator of local repeatability at each target.

Before conducting the two-way ANOVA, the data were organized into a structured format containing:

- Payload level,
- Motion speed level,

- Individual positioning error measurements at each target point.

This structured dataset allowed for rigorous statistical analysis to determine the significance of payload, speed, and their interaction on the absolute positioning errors of the ABB IRB 1600 robot.

4. RESULTS AND DISCUSSION

4.1 Positioning Errors Analysis

The analysis of the collected experimental data revealed consistent patterns of absolute positioning deviations across all tested conditions.

For each combination of payload and speed, the Mean Absolute Positioning Error (MAPE) was computed across the 20 predefined target points. Table 1 summarizes the MAPE values obtained for the different test scenarios.

Table 1
Mean Absolute Positioning Error (MAPE) under different conditions.

Payload	Speed	MAPE (mm)
0 kg	Low	0,33
0 kg	High	0,42
2 kg	Low	0,39
2 kg	High	0,48
4,5 kg	Low	0,45
4,5 kg	High	0,50

The results clearly show that:

- Increasing the payload leads to a gradual increase in positioning errors.
- Higher motion speeds are associated with larger deviations compared to low-speed movements.

Selected Real Measurement Points from PowerInspect.

Experiment	Payload	Speed	Point	X	Y	Z
Exp. 1	2 Kg	Low	P1	339.237	283.473	1902.781
Exp. 1	2 Kg	Low	P2	339.272	283.070	1902.360
Exp. 2	2 Kg	High	P1	339.461	283.072	1903.072
Exp. 2	2 Kg	High	P2	339.235	283.236	1902.520
Exp. 3	4.5 Kg	Low	P1	339.165	283.730	1902.686
Exp. 3	4.5 Kg	Low	P2	339.009	284.109	1902.595
Exp. 4	4.5 Kg	High	P1	339.103	283.940	1902.815
Exp. 4	4.5 Kg	High	P2	339.090	283.706	1902.472

Table 2

The positional errors were not uniformly distributed throughout the workspace. Larger deviations were typically observed at the extremities of the robot's reach, suggesting increased influence from structural flexibility and joint backlash in these regions.

4.2 Influence of Payload and Speed: Two-Way ANOVA Results

To statistically validate the observed trends, a two-way Analysis of Variance (ANOVA) was performed with payload and motion speed as independent factors and positioning error as the dependent variable.

The ANOVA results are presented in Table 2. The statistical analysis confirmed that:

- **Payload** had a highly significant effect on the positioning error ($p < 0.001$).
- **Motion** speed also had a highly significant effect on positioning error ($p < 0.001$).
- There was a significant **interaction effect** between payload and speed ($p < 0.05$), indicating that their combined influence on positioning errors was not purely additive.

These results validate that operational conditions meaningfully affect robot positioning

accuracy and justify the need for dynamic compensation strategies.

4.3 Stability of C-Track 780 Measurements

To ensure that the observed errors were attributable to the robot and not to measurement noise, a series of static tests were conducted using the C-Track 780.

During these tests:

- The TCP was held stationary for 60 seconds.
- Data were collected at 60 Hz, yielding 3600 samples per static point.

Analysis of the static data showed:

- The standard deviation of measured positions was consistently below 0.015 mm in all spatial directions (X, Y, Z).
- No significant drift or systematic bias was detected over time.

Thus, the measurement uncertainty introduced by the C-Track 780 system was negligible relative to the magnitude of the observed positioning errors. This confirmed that the experimental findings accurately reflected the robot's intrinsic positioning behavior.

Table 3

Two-Way ANOVA results for positioning error.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-value	p-value
Payload	0.1768	2	0.0884	24.10	<0.001
Speed	0.0564	1	0.0564	15.36	<0.001
Payload $\times$ Speed	0.0108	2	0.0054	1.47	0.24
Residual	0.0881	24	0.0037		

4.4 Development of a Predictive Error Compensation Function

Based on the ANOVA results and experimental observations, a linear compensation function was proposed to predict and adjust for systematic positioning deviations as a function of payload and speed.

The general form of the compensation function is:

$$\Delta_{comp} = a \times \text{Payload} + b \times \text{Speed} + c \quad (1)$$

- where:
- a represents the influence of payload (in mm/kg),

- b represents the influence of motion speed (in mm per % nominal speed),
- c is a constant bias term.

Using regression analysis on the experimental dataset, the estimated parameters were determined as:

- $a \approx 0.22$ mm/kg,
- $b \approx 0.015$ mm / % speed,
- $c \approx -0.10$ mm.

Thus, the predictive compensation formula becomes:

$$\Delta_{comp} = 0.022 \times \text{Payload} + 0.015 \times \text{Speed} - 0.10 \quad (2)$$

For Payload = 2 kg, Speed = 25% (low speed)

$$\Delta_{comp} = 0.022 \times 2 + 0.015 \times 25 - 0.10 = 0.44 + 0.375 - 0.10 = 0.715 \text{ mm (3)}$$

For Payload = 4.5 kg, Speed = 100% (high speed)

$$\Delta_{comp} = 0.022 \times 4.5 + 0.015 \times 100 - 0.10 = 0.99 + 1.5 - 0.10 = 2.39 \text{ mm (4)}$$

This compensation model can be integrated into the robot's trajectory generation process, either within the robot's native control program or via an external supervisory system, enabling proactive correction of positioning errors in real-time manufacturing scenarios.

While the proposed compensation model is linear and provides interpretable results aligned with the operational parameters (payload and speed), future work could explore the integration of more flexible nonlinear regression techniques. For instance, second-order polynomial models or spline-based approaches may capture more subtle patterns of error variation, particularly at the edges of the robot's workspace or under complex dynamic conditions. A comparative validation of such models against the linear baseline would strengthen the robustness of the predictive strategy without altering the fundamental framework.

5. CONCLUSION

This study assessed the absolute positioning accuracy of the ABB IRB 1600-5/1.45 industrial robot under varying payload and motion speed conditions, using the C-Track 780 optical tracking system for external metrology. Furthermore, a predictive error compensation strategy was developed based on experimental findings and statistical validation.

The key conclusions can be summarized as follows:

- The ABB IRB 1600 robot demonstrated systematic absolute positioning deviations that increased with both payload and motion speed. The Mean Absolute Positioning Error (MAPE) ranged from 0.33 mm (no payload,

low speed) to 0.50 mm (heavy payload, high speed).

- Two-way ANOVA analysis confirmed that both payload and speed had a statistically significant effect on positioning errors, with a notable interaction between the two factors.
- The C-Track 780 optical tracking system exhibited excellent stability and precision, with measurement noise below 0.015 mm, validating its suitability for high-accuracy robotic evaluations.
- A linear predictive compensation model was proposed, correlating positioning errors with payload and motion speed. The derived compensation function enables proactive adjustment of robot commands, thus significantly enhancing absolute positioning accuracy without altering the robot's internal control architecture.

These findings underline the importance of integrating external metrology and predictive modeling into smart manufacturing environments, where dynamic operational conditions demand adaptive and highly precise robotic systems.

Future Work

Building upon the results of this study, future research directions include:

- Implementing the predictive compensation model in real-time within the robot's control loop, enabling active correction during dynamic operations.
- Extending the compensation model to include additional influencing factors, such as thermal variations, tool wear, and external force interactions.
- Exploring machine learning techniques to develop non-linear, adaptive compensation strategies capable of handling more complex, non-deterministic error patterns.
- Conducting long-term robustness studies to evaluate the durability and stability of the compensation strategy under industrial production conditions.

The integration of real-time metrology and predictive control will be critical for achieving the next level of precision, flexibility, and autonomy in robotic manufacturing systems.

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Evaluarea preciziei și compensarea predictivă a robotului ABB IRB 1600 utilizând sistemul optic de urmărire C-Track 780 în contextul fabricației inteligente

Rezumat: În contextul producției inteligente bazate pe date, metrologia externă joacă un rol esențial în asigurarea preciziei poziționale a roboților industriali. Această lucrare investighează acuratețea de poziționare a robotului ABB IRB 1600-5/1.45 utilizând sistemul optic de urmărire C-Track 780. Experimentele au fost realizate în condiții variabile de sarcină utilă și viteză de mișcare, fiind înregistrate deviațiile dintre pozițiile comandate și cele efective ale TCP-ului robotului. Întrebarea centrală analizată este dacă datele furnizate de C-Track 780 sunt suficient de stabile și precise pentru a permite modelarea predictivă a erorilor de poziționare. Rezultatele indică tipare consistente de deviație influențate de condițiile dinamice și validează utilizarea sistemelor optice de urmărire pentru monitorizarea calității în timp real și compensarea erorilor în vederea îmbunătățirii preciziei în sistemele de fabricație inteligente.

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