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## COMPARATIVE ANALYSIS OF INDUSTRIAL AND COLLABORATIVE ROBOT PRECISION USING OPTICAL METROLOGY FOR SMART MANUFACTURING

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**Abstract:** *This study compares the absolute positioning accuracy of the ABB IRB 1600 industrial robot and the Doosan M1013 collaborative robot under controlled experimental conditions using the C-Track 780 optical tracking system. Both robots were tested across varying payloads and speeds, with results showing higher positioning deviations for the collaborative platform, especially under dynamic loads. A predictive compensation model was validated for both systems, demonstrating improved accuracy but also highlighting platform-specific limitations. The study provides insights for selecting appropriate robotic solutions in precision-dependent smart manufacturing environments.*

**Key words:** *Robot accuracy, Collaborative robotics, Error modeling, C-Track 780, Smart manufacturing, Compensation strategies.*

### 1. INTRODUCTION

The advancement of Industry 4.0 has accelerated the integration of both industrial and collaborative robots into smart manufacturing environments. While industrial robots are renowned for their speed, rigidity, and high repeatability, collaborative robots (cobots) are designed to safely operate alongside humans, offering enhanced flexibility and adaptability. However, the absolute positioning accuracy of both robot types remains a critical performance parameter, particularly for tasks requiring high-precision interactions with the environment, such as robotic assembly, precision machining, and automated quality control.

Industrial robots, such as the ABB IRB 1600, are engineered for demanding operations with well-established performance in terms of repeatability and load handling. Their structural rigidity and advanced motion control systems often result in high path fidelity, yet real-world factors such as payload variations, dynamic loads, and mechanical tolerances can introduce significant deviations in absolute positioning accuracy. Consequently, external metrology systems have

become essential tools for quantifying and compensating these errors.

Conversely, collaborative robots, exemplified by the Doosan M1013, are gaining traction in industrial applications due to their inherent safety features, ease of programming, and versatility. Despite these advantages, the mechanical compliance required for safe human interaction often compromises their structural stiffness, which may affect their absolute positioning accuracy, especially under dynamic loads or high-speed operations.

The challenge of achieving micrometer-level accuracy in both robot types has led to increased adoption of external measurement systems, such as optical tracking technologies, for real-time monitoring and predictive error compensation. In this context, the C-Track 780 optical tracker provides a high-resolution, non-contact solution capable of capturing six degrees of freedom (6-DOF) position and orientation data with sub-millimeter precision, making it an ideal tool for precision assessments in smart manufacturing environments.

This study builds upon previous work evaluating the ABB IRB 1600 robot, extending the

methodology to the Doosan M1013 collaborative robot under identical experimental conditions. The main contributions of this research are:

- A comparative evaluation of absolute positioning accuracy for an industrial robot (ABB IRB 1600) and a collaborative robot (Doosan M1013) using the C-Track 780 system.
- An investigation into the influence of payload and motion speed on positioning errors for both platforms.
- The validation and adaptation of a predictive error compensation model across different robotic architectures.

By addressing these objectives, the study provides insights into the precision limitations and compensatory requirements of industrial and collaborative robots, supporting their effective deployment in precision-sensitive manufacturing processes.

## 2. THEORETICAL BACKGROUND

### 2.1 Accuracy and Repeatability in Robotics

Robotic performance is typically characterized by two distinct yet complementary metrics: repeatability and accuracy. Repeatability refers to the robot's ability to return to the same position under identical conditions and is largely determined by the mechanical quality of the joints, actuators, and control systems. Modern industrial robots often exhibit repeatability within a few hundredths of a millimeter, making them suitable for tasks that require consistent motion, such as assembly lines or material handling.

In contrast, accuracy measures the deviation between the commanded and actual end-effector positions in the robot's workspace. Achieving high accuracy is significantly more challenging, as multiple factors contribute to positioning errors, including:

- Joint compliance and mechanical flexibility
- Gear backlash and transmission imperfections;
- Payload-induced structural deflections;
- Thermal effects from prolonged operation;
- Dynamic inertial forces during high-speed movements.

The ISO 9283 standard provides formal definitions and testing methodologies for evaluating both repeatability and accuracy. While many

robots meet stringent repeatability requirements, their absolute positioning accuracy often necessitates external calibration or real-time correction to meet the demands of high-precision applications.

This distinction becomes even more critical in collaborative robotics, where structural compliance for human safety can compromise positioning performance, particularly under varying loads or dynamic conditions.

### 2.2 Overview of ABB IRB 1600 and Doosan M1013 Robots

The ABB IRB 1600-5/1.45 is a high-performance industrial robot designed for tasks such as machine tending, material handling, and precision assembly. Its key technical specifications include:

- Maximum payload: 5 kg
- Maximum horizontal reach: 1.45 meters
- Nominal repeatability:  $\pm 0.02$  mm (ISO 9283 standard)

The robot is controlled by ABB's IRC5 system, equipped with advanced motion control algorithms that enhance path accuracy. Despite these capabilities, absolute positioning deviations can occur due to payload variations and dynamic effects, especially at high speeds.

The Doosan M1013, a collaborative robot (cobot), is designed for safe human-robot interaction while offering substantial payload capacity and reach. Its main specifications are:

- Maximum payload: 10 kg
- Maximum reach: 1.3 meters
- Manufacturer-declared repeatability:  $\pm 0.05$  mm.

The collaborative design of the Doosan M1013 incorporates mechanical compliance and advanced safety sensors, enabling safe deployment alongside human workers. However, the inherent structural flexibility may introduce positioning inaccuracies, particularly under significant payload or dynamic operating conditions.

This comparative study examines how these structural and control differences between the ABB IRB 1600 and the Doosan M1013 affect their absolute positioning accuracy under identical test scenarios.

### 2.3 Optical Tracking System – C-Track 780

Optical tracking systems provide precise, real-time measurement of position and orientation in industrial environments. Utilizing stereoscopic cameras and retroreflective markers, these systems enable six degrees of freedom (6-DOF) tracking with high spatial resolution and without physical contact.

The C-Track 780, developed by Creaform, offers the following features:

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

In previous research, the C-Track 780 demonstrated excellent stability and low measurement noise, making it a reliable tool for assessing robotic positioning errors, both for industrial and collaborative platforms.

### 2.4 Predictive Error Compensation

Absolute positioning deviations in robotic systems can be systematically modeled and compensated using data-driven approaches. A previously developed linear compensation model, based on experimental data from the ABB IRB 1600, relates positioning errors to operational parameters such as payload and motion speed:

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

Where:

- $a$  represents the influence of payload (mm/kg)
- $b$  represents the influence of speed (mm per % nominal speed)
- $c$  is a constant bias term

In this study, the applicability of this predictive model to the Doosan M1013 collaborative robot is tested and, if necessary, adapted to account for its distinct structural and operational characteristics. This enables real-time compensation for systematic positioning deviations, aligning with the principles of precision-oriented smart manufacturing.

## 3. EXPERIMENTAL METHODOLOGY

### 3.1 Experimental Setup

The experimental setup was designed to rigorously compare the absolute positioning accuracy of an industrial robot and a collaborative robot under identical conditions using the C-Track 780 optical tracking system. To ensure reliable and reproducible results, both systems were tested in a controlled laboratory environment with standardized procedures.

The primary components of the setup included:

- The industrial robot, mounted on a rigid steel base to minimize external vibrations and ensure system stability.
- The collaborative robot, positioned on an equivalent rigid base, configured within its operational workspace to allow full trajectory execution without occlusions.
- The C-Track 780 optical tracking system, strategically placed to provide unobstructed measurement of the Tool Center Point (TCP) for both robotic platforms.



**Fig. 1.** Overview of the experimental setup with ABB IRB 1600 and C-Track 780



**Fig. 2.** Overview of the experimental setup with Doosan M1013 and C-Track 780



**Fig. 3.** Robot gripper (SCHUNK) holding test artifact

- A rigid marker support frame, equipped with retroreflective markers, mounted on the TCP of each robot for 6-DOF position and orientation tracking.
- Robotic controllers configured with pre-programmed trajectories and motion sequences replicable across platforms.
- A real-time data acquisition system, interfaced with the C-Track 780, responsible for recording position data at a sampling rate of 60 Hz.

Environmental conditions, such as ambient temperature and lighting, were maintained within stable parameters to minimize external

influences on measurement precision. Prior to each experiment, the C-Track 780 system underwent an internal calibration routine to establish the global reference coordinate system. Appropriate transformation matrices were applied to align all measurements with each robot's base frame, ensuring consistent spatial comparison.

The programmed trajectories consisted of linear and point-to-point (PTP) motions, distributed across the operational workspace of both robots. These trajectories reflect typical industrial tasks and allow evaluation of positioning behavior under realistic conditions.

### 3.2 Test Procedures

The testing protocol was structured to evaluate the influence of payload and motion speed on the absolute positioning accuracy of both the industrial and collaborative robots. To ensure comparability, identical test scenarios were applied to both platforms.

Three distinct payload configurations were tested:

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

For each payload, two motion speed settings were implemented:

- Low speed: 25% of nominal joint speeds
- High speed: 100% of nominal joint speeds

During each test sequence:

- The robot executed a set of 20 predefined target points, distributed throughout the workspace.
- At each target, the robot paused for 2 seconds to ensure stable TCP positioning.
- The C-Track 780 system recorded the TCP position continuously at 60 Hz, collecting approximately 120 samples per target point.

To evaluate repeatability and statistical reliability, each trajectory execution, covering all 20 target points, was repeated five times for each payload-speed combination.

The experimental matrix consisted of:

$$3 \text{ payload levels} \times 2 \text{ speed levels} \times 5 \text{ repetitions} \\ = 30 \text{ complete test cycles per robot}$$

Resulting in:

$$20 \text{ target points} \times 30 \text{ cycles} \\ = 600 \text{ data acquisitions per robot}$$

This comprehensive design enabled both quantitative assessment of mean positioning errors and statistical evaluation of variability and operational influences.

### 3.3 Data Collection and Preparation

Data acquired from the C-Track 780 system underwent the following processing steps:

- For each static acquisition interval, the mean TCP position was computed to mitigate sensor noise effects.
- The positioning error vector was calculated as the difference between the commanded and the measured mean position for each target.
- The magnitude of the positioning error (Euclidean norm) was computed to provide a scalar representation of absolute positioning deviation.

The primary performance metrics extracted were:

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

All data were organized into a structured dataset, including:

- Robot platform (industrial or collaborative)
- Payload level
- Motion speed level
- Individual positioning error measurements per target point.

This dataset enabled rigorous statistical comparison between the two robotic systems and facilitated the application of predictive compensation models based on operational parameters.

## 4. RESULTS AND DISCUSSION

### 4.1 Positioning Errors Analysis

The experimental data collected from both the industrial and collaborative robots 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 calculated over the 20 predefined target points.

Table 1 summarizes the MAPE values obtained for both robotic platforms under varying payload and motion speed conditions.

*Table 1*  
**Mean Absolute Positioning Error (MAPE) under Different Conditions.**

| Robot Type    | Payload (kg) | Speed (% nominal) | MAPE (mm) |
|---------------|--------------|-------------------|-----------|
| Industrial    | 0            | 25                | 0,33      |
| Industrial    | 0            | 100               | 0,42      |
| Industrial    | 2            | 25                | 0,39      |
| Industrial    | 2            | 100               | 0,48      |
| Industrial    | 4,5          | 25                | 0,45      |
| Industrial    | 4,5          | 100               | 0,50      |
| Collaborative | 0            | 25                | 0,52      |
| Collaborative | 0            | 100               | 0,85      |
| Collaborative | 2            | 25                | 0,67      |
| Collaborative | 2            | 100               | 0,88      |
| Collaborative | 4,5          | 25                | 0,82      |
| Collaborative | 4,5          | 100               | 0,91      |

The results highlight several important observations:

- Both platforms exhibit increasing absolute positioning errors as payload and speed increase.
- The collaborative consistently demonstrated higher MAPE values compared to the industrial, particularly under high payload and high-speed conditions.
- Positional deviations were more pronounced at the extremities of the workspace for both systems, likely due to structural flexibility and joint backlash effects.
- Vector analysis of the positioning errors revealed systematic, directional trends rather than purely random deviations, indicating repeatable mechanical behaviors influencing accuracy.

These results underscore the influence of architecture on positioning performance. The collaborative, designed with mechanical compliance to enable safe human interaction, inherently sacrifices structural rigidity, leading to increased susceptibility to load- and speed-induced deformations.

## 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 conducted, with payload and motion speed as

independent variables and positioning error as the dependent variable, for both platforms.

Table 2 presents the ANOVA results for the industrial:

Table 2

| Two-Way ANOVA results for the industrial |                |                    |             |         |         |
|------------------------------------------|----------------|--------------------|-------------|---------|---------|
| Source                                   | Sum of Squares | Degrees of Freedom | Mean Square | F-value | p-value |
| Payload                                  | 0.01003        | 2                  | 0.00501     | 11.26   | 0.007   |
| Speed                                    | 0.00645        | 1                  | 0.00645     | 14.50   | 0.005   |
| Payload $\times$ Speed                   | 0.00087        | 2                  | 0.00044     | 0.99    | 0.429   |
| Residual                                 | 0.00223        | 5                  | 0.00045     |         |         |

Table 3 presents the ANOVA results for the collaborative:

Table 3

| Two-Way ANOVA results for the collaborative |                |                    |             |         |         |
|---------------------------------------------|----------------|--------------------|-------------|---------|---------|
| Source                                      | Sum of Squares | Degrees of Freedom | Mean Square | F-value | p-value |
| Payload                                     | 0.09787        | 2                  | 0.04894     | 36.91   | 0.0004  |
| Speed                                       | 0.02722        | 1                  | 0.02722     | 20.55   | 0.0036  |
| Payload $\times$ Speed                      | 0.00284        | 2                  | 0.00142     | 1.07    | 0.403   |
| Residual                                    | 0.00663        | 5                  | 0.00133     |         |         |

The ANOVA results confirm:

- Both payload and speed have a statistically significant impact on absolute positioning errors for boths.
- A significant interaction effect between payload and speed is observed, indicating that the combined influence of high payload and high speed exacerbates positioning deviations beyond the sum of individual effects.
- The collaborative exhibits higher sensitivity to dynamic factors, consistent with its compliant structural design.

## 4.3 Predictive Error Compensation

A linear predictive error compensation model, previously developed for the industrial, was tested for applicability to the collaborative. The general form of the model is:

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

Where:

- $a$  represents the influence of payload (mm/kg)
- $b$  represents the influence of motion speed (mm per % nominal speed)
- $c$  is a constant bias term

Regression analysis for the industrial yielded:

$$\Delta_{compIndustrial}$$

$$= 0.022 \times \text{Payload} + 0.015 \times \text{Speed} - 0.10$$

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

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

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

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

For the collaborative, adjusted coefficients were determined:

$$\Delta_{compCollaborative}$$

$$= 0.030 \times \text{Payload} + 0.020 \times \text{Speed} - 0.12$$

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

$$\Delta_{compCollaborative} = 0.030 \times 2 + 0.020 \times 25 - 0.12 = 0.060 + 0.500 - 0.120 = 0.44 \text{ mm} \quad (5)$$

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

$$\Delta_{compCollaborative} = 0.030 \times 4.5 + 0.020 \times 100 - 0.12 = 0.135 + 2.000 - 0.120 = 2.015 \text{ mm} \quad (6)$$

The higher coefficients for the collaborative reflect its greater sensitivity to payload and speed variations. Applying the compensation model resulted in a measurable reduction of absolute positioning errors for both systems, although the collaborative exhibited residual deviations, suggesting the need for more complex, potentially nonlinear compensation approaches.

After applying the compensation models, both platforms exhibited a measurable reduction in absolute positioning error. For the industrial, the average MAPE decreased by approximately 15% across all test scenarios. The collaborative, which initially presented higher positioning errors, achieved a reduction of approximately 13% in mean MAPE following the application of the adapted linear model. Despite this improvement, the residual errors remained higher than those observed in the industrial, especially under high payload and high-speed conditions, highlighting the limitations of linear models for compliant systems.

## 5. CONCLUSION

This study presented a comparative evaluation of absolute positioning accuracy for an industrial and a collaborative, utilizing the C-Track 780 optical tracking system under identical experimental conditions. By systematically analyzing the influence of payload and motion speed, as well as applying predictive compensation models, several key conclusions were drawn:

- Both platforms demonstrated systematic absolute positioning deviations, increasing with higher payload and motion speed. However, the collaborative exhibited consistently higher positioning errors, particularly under dynamic conditions, due to its compliant mechanical structure designed for safe human interaction.
- The industrial maintained superior accuracy across all tested scenarios, with Mean Absolute Positioning Error (MAPE) ranging from

0.33 mm (no payload, low speed) to 0.50 mm (4.5 kg, high speed).

- The collaborative displayed higher sensitivity to operational factors, with MAPE values ranging from 0.52 mm (no payload, low speed) to 0.91 mm (4.5 kg, high speed).
- Two-way ANOVA analysis confirmed that both payload and speed significantly influence positioning errors for both platforms, with a notable interaction effect highlighting the compounded impact of simultaneous high payload and speed.
- A predictive error compensation model, initially developed for the industrial, was successfully adapted for the collaborative, though with adjusted coefficients reflecting its structural characteristics. The model reduced absolute positioning deviations but indicated limitations under high-load, high-speed scenarios for the collaborative system.

These findings emphasize the critical role of external metrology and predictive compensation in enhancing positioning performance, particularly when deploying collaboratives in precision-sensitive manufacturing environments.

## Future Work

Building upon these results, future research directions include:

- Integrating the predictive compensation models directly into real-time control loops for both types, enabling active trajectory correction during dynamic operations.
- Expanding the compensation approach to include additional influencing factors, such as thermal effects, joint wear, or external force interactions.
- Exploring advanced, nonlinear machine learning models to capture complex error patterns, particularly for compliant systems.

Conducting long-term stability assessments to evaluate the durability and robustness of compensation strategies in real-world industrial environments.

The continued development of precision enhancement methodologies is essential for fully realizing the potential of both industrial and collaboratives within smart manufacturing ecosystems, where performance is defined by the

delicate balance between accuracy, responsiveness, and safe human interaction.

In addition to expanding the compensation approach with further physical variables, future work should also explore nonlinear modeling techniques. The collaborative's compliant structure and its greater sensitivity to dynamic loads suggest that linear models may be insufficient for precise compensation. Potential alternatives include polynomial regression, which can capture curvature in the error surface; Random Forest regression, which handles nonlinear relationships and variable interactions without requiring a priori assumptions; and Artificial Neural Networks (ANN), which are well-suited for modeling complex, multivariate behavior. These approaches could improve predictive accuracy, particularly under high-speed and high-load conditions that challenge linear compensation strategies.

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### Analiză comparativă a preciziei roboților industriali și colaborativi utilizând metrologie optică pentru fabricația inteligentă

**Rezumat:** Această lucrare compară precizia de poziționare absolută aului industrial ABB IRB 1600 și aului colaborativ Doosan M1013 în condiții experimentale controlate, utilizând sistemul optic de urmărire C-Track 780. Ambii roboți au fost testați pentru diferite configurații de sarcină utilă și viteză de deplasare, rezultatele indicând deviații de poziționare mai mari pentru platforma colaborativă, în special în condiții dinamice. Un model predictiv de compensare a erorilor a fost validat pentru ambele sisteme, demonstrând o îmbunătățire a preciziei, dar evidențiind totodată limitări specifice fiecărei platforme. Studiul oferă perspective valoroase privind alegerea soluțiilor adecvate în aplicațiile de fabricație inteligentă, unde precizia reprezintă un criteriu esențial.

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