CALIBRATION METHODS OF INDUSTRIAL ROBOTS

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https://doi.org/10.23939/istcmtm2024.01.035

Abstract. Robotization is one of the crucial directions of modernizing today's industrial production. Robotic systems offer solutions to many different challenges. However, their implementation is constrained by limited accuracy, which is inferior to conventional machine tools. A way to improve industrial robots' accuracy is to calibrate them, i.e., eliminate factors that affect accuracy by refining the mathematical models for software correction of manufacturing and assembly errors, as well as elastic and thermal deformations.

This article provides an analysis of the methods of robot calibration, their implementation methodology, the results, and the reasons underlying the specific features of each calibration method.

Key words: Robotics, accuracy, calibration, metrology, modelling

1. Introduction

The robotic research and development era began in the mid-20th century, mainly in the industrial environment. The primary purpose of creating robots is to free humans from doing physically demanding, monotonous, or dangerous manual labor. Robots are widely used in manufacturing, laboratories, traffic management, and search and rescue operations. Robots can be sent into hazardous environments, such as deep-sea exploration, war zones, and space exploration, and perform a variety of tasks like mine disposal or operations inside nuclear reactors, eliminating the potential risk to human life. The main advantage of a robot over a human is that it never gets tired, works continuously without interference, is much more accurate than a human, and, last but not least, never contradicts itself.

A human creates a robot and prescribes an algorithm of actions to it. The developer's professionalism will determine the algorithm's correctness and the absence of errors in the robot's software. Accuracy and repeatability are an essential part of the quality of an industrial robot's performance. The positioning accuracy of industrial robots is one of the most important challenges in robotics.

2. Industrial Robots Main Drawbacks

Industrial robots are known to have low positioning accuracy compared to repeatability. Positioning accuracy decreases with the number of axes of the robotic arm due to the accumulation of errors. The difficulty of improving the positioning accuracy of the manipulator is that it varies depending on the robot's operating modes and is therefore difficult to predict.

3. Goal

The aim is to identify areas for designing calibration systems adaptable to different types of robots, regardless of their application, to select the appropriate calibration method, and to improve the accuracy and repeatability of robot performance.

4. Main Factors that Influence Robot Positioning Accuracy

The definition of a robot's accuracy is typically related to robot positioning, so it is defined as a measure of the robot's ability to reach a given position relative to a fixed absolute coordinate system.

A robot's accuracy correlates with repeatability, which is a measure of the robot's ability to return to a previously achieved and memorized position. In most modern robots, the repeatability is about 0.1 mm, and the absolute positioning accuracy is about 1 mm or even 1 cm for different types of robots. Therefore, the accuracy/repeatability ratio is often in the range of 3 to 2.

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The standard describes procedures for determining and verifying the following characteristics of industrial robots:

- Pose accuracy and pose repeatability;
- Multi-directional pose accuracy Variation;
- Distance accuracy and repeatability;
- Position stabilization time;
- Drift of pose characteristics;
- Path accuracy and path repeatability;
- Path accuracy on reorientation;
- Cornering deviations;
- Path velocity characteristics;
- Minimum posing time.

The importance of performance characteristics for robots varies and corresponds to the robot functioning program. For example, for a robot that performs painting in the automotive industry, the most crucial performance characteristics are those related to path, accuracy, repeatability, and velocity.

The tests described in ISO 9283 standard are primarily intended for developing and verifying individual robot specifications, but can also be used for such purposes as prototype testing, type testing, or acceptance testing. The characteristics of position accuracy and repeatability, as defined there, quantify the differences that occur between a nominal position and an actual position, as well as the variations in actual positions for a series of repeated returns to the nominal position.

The robot's accuracy can be affected by multiple impact factors. H. Kochekali et al. [2] classify them:

- environmental (for example, temperature changes);
- parametric (changes in kinematic parameters, displacement of the zero point of connection, the influence of dynamic parameters, transmission flexibility, friction, and other nonlinearities, including hysteresis and backlash);
- measurement (measurement instrument error, resolution, and nonlinearity of joint position sensors);
- computational (computer rounding errors);
- application (setup errors as well as errors in workpiece position and geometry errors).

The analysis of these impact factors and the elimination of their influence is the subject of intensive research aimed at improving both accuracy and repeatability. However, no generally accepted platform has been adopted. Developers are still working on a commonly accepted procedure and tools to verify the accuracy and repeatability of industrial robots. The examination factors influencing positioning accuracy and repeatability reveal that the errors mentioned above can be largely reduced by calibration [3]. The identified errors can be effectively compensated either by adjusting the controller input or by directly changing the parameters of the model considered in the robot controller. There are:

- static calibration – identification of robot parameters that do not change over time;
- dynamic calibration – identification of parameters while the robot is moving.

Static calibration primarily focuses on correcting geometric parameters such as the geometry of the joint axis and the joint angle offset. Non-geometric parameters include elasticity of joints and links, gear shape errors (eccentricity and transmission errors), gear backlash, and temperature-induced expansion. Both geometric and non-geometric parameters are related to static robot calibration modeling, as the parameters can only be measured from the robot's pose.

After determining the static parameters of the robot, you can perform a dynamic calibration. This type of calibration is performed to define the dynamic characteristics of the robot (e.g., mass distribution in links, friction in actuators and joints, and rigidity of the structure).

5. Calibration Processes Analysis

Robot calibration is a complex process of modeling, measuring, identifying the actual physical characteristics of a robot, and implementing a new model. The calibration procedure first involves the development of a kinematic model in which parameters accurately reflect the actual robot. Then, specially selected characteristics of the robot are measured using measuring instruments with known accuracy. This is followed by a parameter identification procedure, used to calculate a set of parameter values. When entered into the nominal robot model, these parameter values accurately represent the robot performance evaluation. As a result, the robot model within the position control software could be adjusted. It is worth mentioning that there are no guidelines or standards for developing internal calibration procedures and applying specialized metrology instruments.

Therefore, the robot calibration procedure can be divided into four main stages:

1) kinematic model development;
2) pose measurement;
3) parameter identification;
4) software position compensation.

Among the existing methods of kinematic modeling, the Denavit-Hartenberg (D-H) model is widely used in robotics due to its clear physical interpretation of mechanisms and relatively easy implementation in programming robot manipulators. It is well-known a modified version of the D-H model. There was developed also a model as well as a new identification method to evaluate its S-model parameters, based on the analysis of circular joint points. These joint characteristics are the plane of rotation, the center of rotation, and the radius of rotation. A laser tracker was applied to measure position errors, identifying the robot parameters errors. To calibrate the ABB IRB 1600-6/1.45 robot was also used a laser tracker. Moreover, an optimal configuration data permitted to improve the robot's accuracy with a maximum deviation of less than 0.4 mm for any axis. Some works are based only on computer modeling [4]. An adaptive tracking system for an industrial system (ATIR) was developed in the European COMET project to correct robot errors in real-time and to compensate for errors during parts milling [5-6].

The next step is to perform an external precise measurement of the Cartesian pose of the end effector that corresponds to each joint position. Measurements are made in the number of positions sufficient for the process of identifying the end effector (Fig.).

Nowadays, various methods and tools for robot metrology are developed in the manufacturing industry, ranging from the simplest dial indicator, theodolite, and calibration chamber, to the most advanced ones, such as machine vision, portable coordinate measuring machine, laser tracker, and others.

Calibration setup based on a coordinate measuring machine

In [7], a robot calibration procedure has deployed a Krypton K600 camera to measure 25 to 100 poses randomly distributed within the robot's working area, with all the robot's axes moving, is described. The ROCAL software designs a set of evenly distributed poses based on the encoder pose measurement. This set of poses is then converted into a robot program, which is then loaded and executed by the robot. In [8], a vision-based automatic theodolite (VBAT) is described, which is an automatic pose measurement system for robot calibration. The system performs calibration with high velocity, reliability, and repeatability. In [9], calibration is accomplished by controlling the robot's movements and observing the changes in the image coordinates of the calibration map. The robot performed two known movements to obtain three different camera locations for calibration. The standard deviations of the encoder positioning were 0.7, 1.0, and 0.7 pixels, respectively. The system was applied to calibrate the PUMA robot with six degrees of freedom, and the results were compared to another calibration of the same encoder in a coordinate measuring machine with a repeatability and accuracy of 0.02 mm. The VBAT calibration improved the positioning accuracy of the PUMA robot by up to 0.2 mm compared to the CMM calibration accuracy of 14 mm before the calibration.

Two calibration systems are presented in [10]. To measure the Cartesian position of the Puma manipulator's working body, a laser tracking system called Optotrac, developed and manufactured at the University of Surrey, was studied. The system represents two tracking subsystems, with each of them directing a laser beam at a target attached to the robot's end-effector by two orthogonally mounted optical scanner modules. The results of position tracking by the scanners were used to calculate the three-dimensional position of the target. The achieved repeatability of the robot was 0.1 mm. Setting up the Optotrac system is very time-consuming, making it much less efficient for industrial applications than existing industrial solutions such as the Krypton K600 and K400 (Renders, 2006) and Leica Lasertracker LTD 500 (Fixel, 2006).

The second measuring system described is a system using the Krypton K600. The main part of the K-series measuring system is a camera set consisting of three linear CCD cameras. The camera system is based on active LEDs with infrared light. When an LED is selected by the three linear cameras, a computer calculates its exact position in 3D space. The positions are calculated by comparing the images from the 3 linear CCD cameras based on the effect of 3 intersecting planes on the LED, which are then calculated relative to a pre-calibrated camera. According to the manufacturer, the system is capable of tracking up to 256 LEDs simultaneously using computer-controlled strobing. This simultaneous tracking of multiple points allows us to measure the position and orientation of objects by attaching 3 or more LEDs to them and measuring their position simultaneously. The system with a single-point accuracy of up to 60 mm and is capable of measuring targets up to 6 m away from the camera.

The measuring equipment of calibration systems must be appropriately matched in terms of accuracy, speed, and resolution for reliable identification of model parameters.

In [11], an algorithm is proposed to determine the path that gives the desired pose of the end effector of an industrial robot manipulator. The search algorithm gradually approaches the desired configuration by selecting and evaluating several alternative robot configurations. A grid of alternative robot configurations is built studying a set of parameters that reduce the search space to minimize the computation time. The grid resolution and size parameters are set based on the desired result. The model algorithm parameters and grid parameters are tested to reduce the time of the search process to gain a better understanding of the desired robot pose.

In [12], a measurement system based on wire sensors was developed for robot calibration and applied to an anthropomorphic robot with six degrees of freedom. First, the measuring system was optimized for obtaining isotropic accuracy and high sensitivity using modeling tools, and in the next experimental stage, the same system was issued for kinematic robot calibration.

Unlike traditional calibration methods that require expensive equipment and complex steps, [13] presents an online vision-based robot calibration method that requires only a few reference images. This method involves a camera that is rigidly attached to the robot's end effector (EE), and calibration boards must be installed around the robot so that the camera can detect angles from the calibration board images. The detected angles are assessed to evaluate the robot's pose. The kinematic parameters can be automatically calculated based on known robot poses. Compared to existing self- calibration methods, a significant advantage of this online self-calibration method is that the entire robot calibration process is automated and without manual intervention, allowing the robot calibration to be completed online while the robot is operating. Therefore, the proposed approach is highly suitable for unknown environments such as the sea or outer space.

In [14], an error compensation method with error similarity analysis is proposed to improve the absolute positioning accuracy of industrial robots. Error compensation is accomplished by changing the state coordinates in the robot control instructions. Experimental verification showed that the maximum robot positioning error decreased by 75.36% from 1.2912 mm to 0.3182 mm.

In [15], a methodology for autonomous online calibration of an industrial robot based on ultrasonic triangulation is proposed. The parameters of the robot's kinematics are readjusted based on the results of real-time identification. The entire robot calibration procedure is performed automatically and without any manual intervention. Compared to other existing, expensive, and complex approaches, the proposed method allows for more accurate calibration in the short term. In [16], an online self-calibration method for a robot based on an inertial measuring device and a pose sensor is proposed. Compared to existing self-calibration methods, the advantage of this method is that it does not require any complex steps such as camera calibration, angle detection, and laser tracking, which makes the proposed robot calibration procedure more autonomous in a dynamic production environment. Experimental studies on the GOOGOL GRB3016 robot have shown that the proposed method has better accuracy, convenience, and efficiency compared to others.

In [17], an online self-calibration method was developed that is used to evaluate errors in the kinematic parameters of serial robot manipulators. In this method, the position marker and the inertial measuring unit are rigidly fixed to the robot's working body. To eliminate the influence of noise and measurement errors from the sensors, the model articulation controller (CMAC) algorithm was applied to evaluate the robot's pose.

For calculated poses, errors between the actual and nominal kinematic parameters of the robot manipulator can be detected with help of Kalman filter. This method requires only a few simple steps but works with high autonomy and accuracy. To verify this method, several experiments have been conducted with the GOOGOL GRB3016 robot, and the results show that it is indeed highly convenient, precise, and efficient.

In [18], a method of external calibration of the camera and laser rangefinder using a calibration cube is presented. The calibration is based on the observation of three edges of the cube from the camera and three laser dots projected onto the edges with a laser. The equations for the external calibration parameters, rotation matrix, and displacement vector are based on the constraint that, in image coordinates, the projection of a laser point onto the image plane lies on the projection of three edges of a cube. The parameters are calculated with three changes in the position of the cube. Experimental results show that the proposed method is reasonably accurate.

In [19], an artificial neural network (ANN) was presented to compensate for both residual positioning and orientation errors. An automatic measurement procedure was developed and nearly 14,000 robot poses were measured with help of a laser tracker. To determine the best ANN parameters, a five-fold cross-validation of the training data was applied. These tests indicate that greater accuracy can be achieved by combining geometric calibration and ANN. Applying such a combination to the test data reduced the maximum/average encoder position error to 6.28%/4.26% and the maximum/average orientation error to 7.41%/3.34% of the initial values (uncalibrated).

Summarizing, various methods for calibrating robots have been introduced and analyzed, with consideration of their respective advantages and disadvantages Based on this information, you can make an informed decision when choosing a robot calibration method and follow the instructions and recommendations provided by manufacturers or component developers. Additionally, it is necessary to confirm and verify the calibration results using various tests and scenarios and to repeat and refine the calibration when necessary, especially when components or the robot's environment changes.

6. Analysis of positioning error in a robot control system

Robot joints are the main components in a robotic system that play a crucial role in the mobility and functionality of robots, especially in ensuring the accuracy of the end effector positioning. Robot joints are those points of articulation that allow a robot to mimic human joints, such as elbow and knee joints. They are assembled from mechanical and electrical components that contributes to the overall functionality and performance of the joint. When the electrical components are integrated into the robotic joint, they form a closed-loop control system. This contributes to perform precise and controlled movements, adapt to changes in the environment, and perform complex tasks autonomously.

Understanding the physical principles that determine the way robotic joints work is essential to effectively design and control these components. These principles can be categorized into kinematic and dynamic models, which together form the foundation of a robotic system. For example, kinematic equations can be studied to calculate joint position, velocity, and acceleration based on input from a motor or drive. This information is useful in developing control algorithms that ensure that the joint moves accurately and smoothly, following the desired trajectory or path. One of the key concepts is the dynamic model of the joint, which is a mathematical representation of the joint's motion given the applied forces or torques. This model typically includes terms related to joint inertia, damping (resistance to motion), and stiffness (resistance to deformation), as well as any external forces or torques acting on the joint.

When studying the dynamics of motion, and to reduce the positioning error, it is essential to analyze the relations between the contact forces and the forces acting on the robot mechanisms, as well as to study the effect of acceleration on the robot's trajectory. The kinematic model of the robot includes displacement, velocity, acceleration, and time, while the dynamic analysis includes the generalized forces of the actuators with the energy added to the system. There are various theories regarding the dynamic model of robot navigation, but a common form of dynamic study is the analysis of forces and moments that occur inside and outside the system. The general equations of motion of the system, and even the analysis of the moments and energy of the system, allow us to develop a dynamic model of the robotic system. In this analysis, it is important to consider the physical and geometric characteristics of the system, such as mass, size, diameter, and others, which are represented in moments of inertia, as well as the static and dynamic torques of the system.

Each robot joint consists of an actuator (DC motor, AC motor, or stepper motor) connected to a speed reducer and sensors to measure position and velocity. These elements can be absolute or incremental encoders at each joint. Robot motion control is a complex issue because the movement of a mechanical structure is accomplished through rotation and movement of joints that are controlled simultaneously. Additionally, the behavior of the structure is nonlinear and depends on the operating conditions. These conditions are considered while choosing a motion control strategy. The desired motion trajectory is determined by position, velocity, acceleration, and orientation, so it is necessary to perform coordinate transformations at a given time at a significant computational complexity. Typically, robot control only considers the kinematic model of the joints, and each joint must be controlled independently.

As for the dynamic model, simple analytical models often do not take into account the stiffness and elasticity of the joints, or, if they do, they approximate the linear behavior of the model with coefficients that are inherent in a high uncertainty. Other nonlinear effects, such as backlash and friction, are often not considered. The dynamics of these effects question the accuracy of the model, as they are also influenced by environmental conditions.

In practice, various robot control methods are applied to reduce positioning errors. Therefore, control systems play an important role in the performance of robotic joints, ensuring that the joints move accurately and smoothly according to the desired motion path. There are two main types of control systems developed in robotics: open-loop and closed-loop control systems [23].

Open-loop control systems are relatively simple because they do not rely on feedback from the joint to adjust the control signal. Instead, the control input signal, such as motor voltage or current, is determined based only on the desired joint position, speed, or acceleration. In an open-loop control system, the control algorithm calculates the required motor power based on the desired movement and the dynamic model of the joint. This signal is sent to the motor, which drives the joint to a specific position. However, since there is no feedback from the joint, the control system cannot correct any errors or interference that may occur during movement, such as friction, play, or external forces. Open-loop control systems have several drawbacks. They are highly sensitive to errors in the dynamic model of the joint, as any inaccuracies in the model can lead to significant deviations from the programmed pose. Furthermore, open-loop control systems cannot adapt to changes in the joint properties or the environment, such as part wear, temperature fluctuations, or external interference.

Closed-loop control systems, unlike open-loop systems, rely on feedback from the joint to continuously adjust the control input. This feedback allows the control system to correct for errors or interference that may occur during movement, resulting in more accurate and consistent joint performance. Closed-loop control systems have several advantages over open-loop systems. They are less sensitive to errors in the dynamic model of the joint, as feedback allows the control system to correct inaccuracies in the model or changes in joint properties. Additionally, closed-loop control systems can adapt to external disturbances such as friction, backlash, or external forces, ensuring that the desired joint motion is maintained even when these disturbances are present. It's important to note that closed-loop control systems use a differential signal between the input and output for control, which is never zero, resulting in positioning error.

However, closed-loop control systems are more complex than open-loop systems because they require additional components such as sensors providing feedback. Closed loop control systems can also be more susceptible to issues such as sensor noise, delay, or signal instability, which can affect connection performance and require careful adjustment of the control algorithm. These systems are crucial to the functioning of robotic joints because they control the movement and coordination of these joints. They ensure that the joints move accurately to the desired positions, maintain the correct speed and torque, and adapt to any changes in the task space or environment.

Advanced robot control methods are becoming more widely available as computing power increases and the cost of computing resources decreases significantly. However, the dynamic model of a robot contains uncertainties in some parameters, and many control methods are sensitive to their values, especially during high-speed operations. Therefore, the process of calibrating robots remains relevant.

7. Conclusions

1 Analyzing the above review papers and articles on calibration methods, one can see that each degree of manipulator mobility is a closed loop, but the robot as a whole remains an open system in terms of controlling the position of the encoder in world coordinates. This leads to the fact that the manufacturing and assembly errors of the manipulator are not considered by the control system. From the point of view of control theory, it is necessary to close the feedback loop using the sensors of the working body position in the inertial coordinate system to reduce the absolute error of the robot. However, at the current level of industrial robotics development, such a control system is too complex and expensive or is not capable of operating in real time.

2 The application of measuring machines for calibration provides high accuracy, but is costable. While stereo triangulating (coordinates of a three-dimensional point), the working body's positions are determined with help of theodolites.

3 Non-contact methods with ultrasonic, optical, or other types of sensors aplication complicate the calibration process in the working environment.

4 It is important to note that the self-calibration technique is divided into two groups: the redundant sensor approach and the motion-restricted approach. The redundant sensor approach requires one or more redundant rotary sensors on the corresponding passive joints of the manipulator. In the motion-restricted approach, the mobility of the resulting self-calibration system is lower than its degree of sensitivity, since one or more passive joints are fixed or the partial degree of freedom of the manipulator is limited to allow the calibration algorithm to be performed.

5 In the case of online calibration, training the robot is time-consuming and therefore creates a negative balance between programming time and production time. Low production volumes, part complexity, or frequent new product introductions require a significant amount of time to learn. In addition, online learning is inflexible - the entire operation must be repeated, even if there are minor changes to the robot's path. Online programming seems to be the best method if the manufacturing facility produces a single product with a high volume and limited functions. Artificial intelligence allows robots to adapt to unknown situations, tasks, and objects, but it should be noted that since this approach is still evolving, it often deals only with simplified situations and is therefore unreliable. While applying artificial intelligence for calibration, a lot of time is needed for training.

8. Acknowledgment

The authors thank the Editorial Board of the Scientific journal “Measuring Equipment and Metrology” for their support.

9. Mutual claims of authors

The authors state that there are no financial or other potential conflicts regarding this work.

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