INFORMATION AND MEASUREMENT TECHNOLOGIES IN MECHATRONICS AND ROBOTICS

FACTORS AFFECTING THE ACCURACY AND REPEATABILITY OF INDUSTRIAL ROBOT POSITIONING

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Abstract. Industrial robots refer to the most complex products of mechanical engineering and electronic equipment in terms of their labor intensity, accuracy, and a class of manufacture as well as quality requirements. Both static and dynamic positioning inaccuracies occur during their operation. Static positioning depends mainly on such parameters as joint axis geometry and angle offset. Non-geometric parameters include compliance (elasticity of joints and bonds), gear form errors (eccentricity and gear errors), gear backlash, and temperature-related expansion. Dynamic positioning is only relevant for large robots that are subject to high speeds and accelerations. Positioning accuracy is affected by the design features of the robot, the control system, the speed of movement and rotation of the manipulator, temperature, and vibrations, both inherent and caused by the robot's location in production. This research examines the sources of positioning inaccuracy and gives recommendations for improving the positioning characteristics of robots.

Key words: Robotics, Static and dynamic positioning, Inaccuracy, Mechanical characteristics.

1. Introduction

Robotics promises to change the principle of civilization in such areas, as industry, medicine, agriculture, communication, and transport. Successes of robots equipped with powerful executive mechanisms and effective control algorithms, permit the application of robots in various spheres of life, and in addition, including in search and rescue operations. Robots produced by industry differ in various designs, technical characteristics, fields of application, etc. To establish a rational area of application of robots is necessary to know the basic technical characteristics [1].

2. Drawbacks

The evolution of industrial robots is constantly increasing their accuracy and repeatability. However, when robotics moves from the laboratory to mass production, problems such as system performance, accuracy, reliability, etc. arise. One of the obstacles is the insufficient repeatability of robot positioning. The positioning accuracy of industrial robots is one of the critical problems in robotics [2-3]. Robots are inherent in low positioning accuracy compared to repeatability. Positioning accuracy decreases with the number of axes of the robotic arm due to the accumulation of errors. At the same time, it is difficult to develop a robotic system that works as efficiently as in living nature due to energy and power limitations, deficiencies in the characteristics of materials, and problems in management.

3. Goal of Article

Study of the influential factors of the repeatability and positioning error of robotic systems, which enables their reduction through calibration.

4. Main influence factors of positioning in robotics

4.1. Determination of accuracy and repeatability of positioning in robotics.

During the operation of an industrial robot of any type, when stopping and fixing its working body at any point in space, an error occurs, which is called a positioning error. This error is random, as it depends on a large number of factors, each of which individually cannot be determined in advance in terms of magnitude or direction of influence. Most often, it is characterized by an absolute error (AR) (Fig. 1). Positioning error – deviation of the given position of the executive mechanism from the actual position during repeated positioning. The positioning error can be measured in linear or angular units.

The international standard ISO 9283 [1] defines various parameters related to some test procedures for industrial robots, including accuracy and repeatability. Its main part deals with the testing of individual characteristics. Specific parameters such as position-to-position characteristics and path characteristics are considered for comparative testing. The standard describes methods for determining and verifying the following characteristics of industrial robots:

- positioning accuracy and position repeatability;
- change in position accuracy depending on the direction of movement;
- distance accuracy and reproducibility;
- position stabilization time;
- drift of position characteristics;
- trajectory accuracy and trajectory repeatability;
- path accuracy during reorientation;

• deviation on turns;
• speed characteristics;
• minimal positioning time.

The importance of operational characteristics for robots is different and corresponds to the program of operation of a specific robot. For example, for a robot that performs painting in the automotive industry, important performance characteristics are related to routing, accuracy, repeatability, and speed.

The tests described in this standard are primarily intended for the development and verification of individual parameters of robots, but can also be used for purposes such as prototype testing, type testing, or acceptance testing [2].

The position accuracy and repeatability characteristics, as defined in this standard, quantify the differences that occur between the nominal position and the actual position, as well as the fluctuations in the actual positions for a series of revisits to the nominal position [4]. These errors can be caused by:

• coordinate conversion errors;

• the difference in the dimensions of the hinged structure from those used in the model of the robot control system;

• mechanical defects such as clearances, hysteresis, friction, and external influences such as temperature.

Position accuracy (AP) is defined as the difference between the position of the nominal position and the barycenter of the real position, Fig. 1. The accuracy of positioning repeatability can be determined by the expression [5-6]:

$$AP = \sqrt{\left(AP_x\right)^2 + \left(AP_y\right)^2 + \left(AP_z\right)^2}$$

here APx, APy, APz are the exact positions along the x, y, and z axes. The 2nd term related to precision is called repeatability (RP) in robotics; it is the property of an industrial robot to return its end effector to the same position, i.e. to achieve repetition of the same task over and over again. Unlike accuracy, which is somewhat subjective depending on application requirements, repeatability is an absolute value. Repeatability is usually the most important criterion for a robot. High repeatability is more desirable than high precision in industrial robot applications.

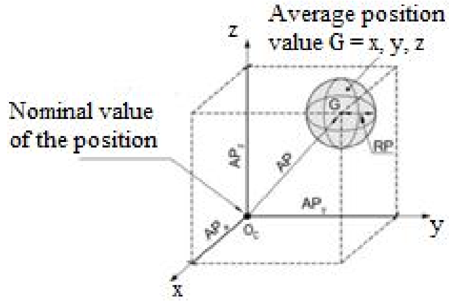


Fig. 1 Image of accuracy and repeatability of positioning (G is an average position value or barycenter; RP describes the repeatability zone)

The accuracy of the industrial manipulator can be divided into absolute positioning accuracy and repeatable positioning accuracy. Most manipulators have high repeatable positioning accuracy, but insufficient absolute positioning accuracy.

4.2. Consideration of influential factors on positioning during robot operation

When the robot is working, it is important to determine its location. For this, systems for determining its position are developed. Robot positioning systems can be divided into categories: mechanical; receiving and transmitting systems (acoustic, electromagnetic, and magnetic). Some of them can measure the position of a stationary robot, while others carry out measurements when the robot is moving. Mechanical systems require physical contact between the robot and the measuring device. Transceiver systems provide measurements of the robot's emitted and reflected signals to compute the angular position and linear distance to the object. Magnetic systems apply the spatial configuration of the Earth's static magnetic fields.

The main components of the mechanical robotic system, which affect the positioning error, are the motor, the control system, the encoder, and the wave reducer. The speed of the executive mechanism of the robot is determined by the motor and the transmission ratio of the wave gear. In this chain, the positioning error between the encoder and the final result, including the wave reducer, is formed. Encoders are placed on the motor shafts, and a high-ratio wave gear is used to reduce the speed of the shaft. So, repeatability is mainly affected by hysteresis, backlash, torsional elasticity, and gear friction. These errors are associated with the displacement value provided by the encoders of the robot's active joint. They represent the difference between the movement fixed by the sensor and the actual movement performed by the joint. These differences are mainly caused by the sensors' errors themselves and the offset caused by the zeroing (or initial position) of each active connection (i.e., the error in the zero or base position of the active connection). The resolution of the encoder previses the small effect on the repeatability of the final positioning. While considering the long duration of the encoder usage, repeatability can be affected by its thermal expansion.

The sources leading to the loss of absolute accuracy are the errors caused by the length of the joint links, the non-parallelism of the axes, the gap between the gears, the base offset, and manufacturing errors. Errors that occur when assembling robots are classified as geometric errors and account for approximately 90% of all errors value. The remaining 10% of errors are attributed to the payload, thermal deviation, gear backlash, servo error, etc. They are classified as non-geometric errors [1].

The first step in the improvement of the accuracy and repeatability of industrial robots is to study the current state of robotics technology and other related technologies, such as metrology subsystems. Let's consider in more detail the components that affect positioning accuracy and the corresponding factors that have the greatest impact on its values.

Control system error.

Motion control of the robot allows the articulated elements of the robot to move with the help of rotary and sliding joints. Robot management can be divided into 3 levels that make up the management hierarchy:

- Actuator control, or control of each axis of the robot separately.
- Trajectory control, or robot arm control with coordination between axes to form the required path.
- Control of hand movement in coordination with the environment.

For each of the above levels of robot control, a regulator (for example, proportional-integral-differential, PID-regulator) is recommended; it may be unable to compensate quickly for changes in the payload. As a result, arises a dynamic positioning error with different payload masses. The main factor affecting this error is the accuracy of the feedback sensors. Since the control system and engines operate with errors, as a result of the control error, there exists a difference between the real movement of the links and the calculated ones. The difference between the actual and calculated values of the actuator coordinate, which is caused by the error of the control system and motors, is the positioning error.

In addition, there is another error caused by the inability of the robot control system to recognize the difference in the two positions of the executive mechanism, i.e. the conditional distance between which is smaller than the bit size of the operating system.

The error caused by the coordinate transformation

For any industrial robot, a certain coordinate system is an essential element for the correct functioning of the program. There exist different coordinate systems for industrial robots. Widely used methods of coordinate transformation are based on solving cloud point equations. The movement of the joints of the manipulator, the operation of the tool, or the grip of the robot can be described to implement several control functions, including autonomous programming, program setup, motion coordination of multiple robots, and more. The raw data should be transformed into a single coordinate system for the convenience of further data collection, comparison, and data merging. A slight error caused by inaccurate coordinate conversion can cause problems such as robot malfunction, poor image alignment, and more. Especially in the error-accumulating system of industrial robots, the coordinate transformation error accumulates at each step and thereby reduces the positioning accuracy.

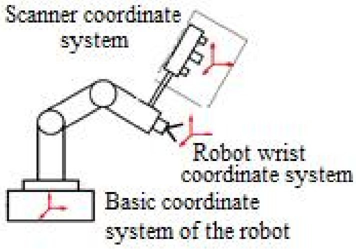


Fig. 2 Transformation of coordinates in the robot scanner system

Figure 2 shows an example of several coordinates in the robotic system. The critical process of matching the coordinate axes is obtaining the matrices of transforming point clouds into a single coordinate system. In the robot arm and scanner (eyes), the coordinate transformation is carried out to determine the matrix of the scanner coordinate system into the robot wrist coordinate system with minimal conversion error. The coordinate data obtained in each position for the given example can be adjusted to the basic coordinate system of the robot using two-coordinate transformations [2]. With an inaccurate method, the transformation error can be combined with the kinematics parameters, lowering positioning accuracy due to the parameters' calibration. Therefore, an accurate coordinate transformation method is indispensable in robot calibration.

Geometric error

The processes leading to changes in the initial properties of the robotic system occur in the materials from which the elements are made, as well as in the lubricants involved in the operation process. The geometric error arises due to inaccuracies in the assembly and processing of its primary nodes. It includes the deviations in the linear dimensions of the links and the shape of their longitudinal axes from the specified values. The sequential mechanism of the manipulator increases the error step by step from the base to the actuator.

The precision gearbox is the main component of an industrial robot and largely determines the performance of the robot. The precision gearbox often makes a reciprocating movement, which leads to deviations in the input and output angles of the elements of the robotic system. This seriously affects the accuracy and dynamic characteristics of the entire robot.

Precision transmission systems in robotics must have high torque and positioning accuracy, compact designs, and can be operated in extreme conditions. These requirements provide gears with wave deformation. The wave drive is a kind of mechanism consisting of 4 critical components: a wave generator, a flexible ring, a bearing, and a rigid ring (Fig. 3).

When analyzing the operation of a wave gear, it is difficult to measure and model the gap between the elements, because it is combined with kinematic errors and therefore difficult to separate them. The error of the wave gear is determined based on its components, which include the radial size error and the radial run-out error of the wave generator, the geometric eccentricity error, and the motion eccentricity error, which is caused by the processing and installation of the rigid and flexible gears, the backlash error caused by the backlash between the rigid and flexible gears. These errors are periodic, which lead to changes in the gear ratio, and kinematic error, caused by manufacturing and assembly errors.

From the above, it can be concluded that it is not possible to determine the general laws of the influence of geometric errors. In each specific case, a separate study should be conducted, since the impact of geometric errors depends on the architecture, dimensions, and working space of the robot.

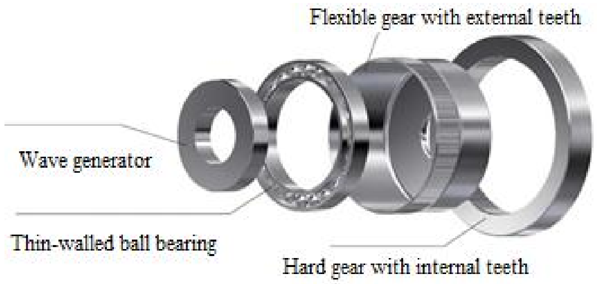
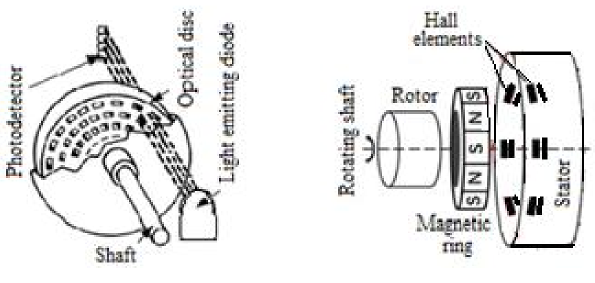


Fig. 3 Structure of the wave reducer

Thermal errors

Encoders convert motion into an electrical signal that can be read by a control device in a motion control system. The encoder sends a feedback signal that can be used to determine position, speed, or direction. The control device can use this information to send a command to perform a specific function.



a *б*

Fig. 4. Design of optical (a) and magnetic (b) encoders

For optical encoders, an increase in temperature causes a decrease in the light transmission of the LED. Thermal expansion can narrow the air gap between the disc and the light source, or shift the optical disc and cause pulses to drop. Extreme cases of such thermal expansion can lead to component contact and damage the encoder (Fig. 4a). Magnetic encoders are inherent in the lower accuracy and resolution, but they are simpler in design and less demanding in operating conditions. In magnetic encoders, thermal expansion and contraction of the magnetic wheel can change the pitch of the magnetic poles and thus change the output code (Fig. 4b).

Thermal effects can also affect the accuracy of high-precision robots. It has been studied that to obtain nanometric accuracy of movements, it is necessary to maintain the temperature with an accuracy of 0.01 ° C [5].**Error caused by gravity.** Deformations of robot elements caused by gravity can be significantly similar in size to geometric errors in a small working space. The low loading capacity and accuracy are due to the architecture of the existing manipulators and, in particular, the sequential arrangement of their links. Each of them carries the weight of the next segment in addition to the payload, so they are subjected to large bending moments, increasing stiffness requirements. The source of positioning errors is a violation of the specified geometric ratios between the axes of the links. The sequential arrangement of the links together with the requirement for their rigidity means that the moving parts of the robot have to be massive. As a result, during high-speed movements, the manipulator is affected by inertia forces, centrifugal forces, and Coriolis forces, which complicates the control of the robot and leads to positioning errors.

In practice, the studied methods of determining robot positioning errors are divided into 3 groups [7-8]:

a) Method based on the requirements of [1]. Here, to determine the repeatability error of the positioning, a series of measurements must be carried out at the most difficult points of its working space and with a full load. Robot manufacturers apply this method. Nevertheless, it is not convenient since limited information can be obtained.

b) Methods using neural networks. They are related to the development of modern software [9]. Recently, the number of studies in the high-mentioned area aiming the determination of the repeatability error of robot positioning has increased [10] even though experiments need the high-precision and therefore they are difficult to implement in industrial conditions. For high-quality and proper training of neural networks, it is necessary to collect a large amount of data. Many measurements must be made to obtain such data over the entire area of the robot's space. It takes a lot of time and requires complex measuring equipment.

c) Methods based on robot kinematics studies of positioning repeatability errors; they consider the extreme values of the error of joint coordinates $\pm\Delta q_i$.. Problems associated with their application include the issue of determining the value of $\pm\Delta q_i$ and the fact that the results obtained have the form of so-called polyhedra or polygons of positioning repeatability. They only provide the estimation of the area within which the manipulator can stop (it is assumed that there is even a probability distribution for a random error inside the polygons). While analyzing, it is necessary to assume the maximum values of errors, which can be extremely unlikely. Similarly, estimating the value of $\pm\Delta q_i$ can be a problem. Assuming that the distribution of errors in establishing common coordinates obeys the Gaussian distribution, the so-called three-sigma rule can be applied. However, actual distributions can sometimes deviate slightly from the normal distribution law (when skewness coefficients are non-zero); then assuming this rule (for model inputs) can lead to erroneous results. The interpretation of the adequacy of the model also causes certain difficulties, since the measurement results, as a rule, processed with the help of statistical measurements, should be compared with the maximum error of the repeatability of the positioning.

d) it seems quite an interesting method of calibration with help of laser interferometry [3]. Our operating experience of such lasers produced by SIOS [11] in the laser-based calibration system is revealed next. The studied lasers of Laser interferometer SP 5000 NG (for particular calibration) and LM20 industry type have demonstrated the best performance for the last one in the university laboratory conditions. Studies of robot kinematics with their help were complex since the working robot created mechanical shocks (vibration) and electromagnetic interference. Therefore, the solution was to calibrate ultrasonic smart sensors of distance by laser interferometer proceeding their deployment into the robot [12].

5. Summary and Outlook

The analysis of impact factors on the exactness and repeatability of positioning envisages that the specified errors can be significantly reduced due to calibration. Detected errors can be effectively compensated either by adjusting the controller input (target point) or by directly changing the parameters of the model applied in the robot controller. Robot calibration without repositioning or redesigning the robot can be used to improve positioning accuracy in a sequential process that includes modeling, measurement, identification, and compensation steps.

The calibration process itself is divided into three levels. The 1st one is designed to determine the relationship between the joint movement sensor signals and the actual movement of the joint. The 2nd one consists of robot kinematic geometry determination and includes assembly errors, processing errors, and joint offset angle, i.e. deviation of nominal kinematic parameters from real properties. The 3rd one is defined as a "non-geometric" calibration that can account for the effects of servo error, backlash, gearbox friction, elasticity, thermal link deformation, and payload.

Although currently, the positioning accuracy of an industrial robot has to be improved due to progressive design and control approaches, it is still difficult to achieve the required accuracy due to the following reasons:

1) geometric effects, such as small deviations in the shape/size of joints and links of the robot cause significant errors in the final working body;

2) there arise the design contradictions between the weight and stiffness of the link, which makes the design of the link the result of a compromise between the specified characteristics. Otherwise, the geometrical deviations of the joint and link, combined with their weight effects, can cause additional positioning errors under different robot configurations.

6. Gratitude

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7. Conflict of Interest

The authors declare no financial or other potential conflicts related to this work.

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