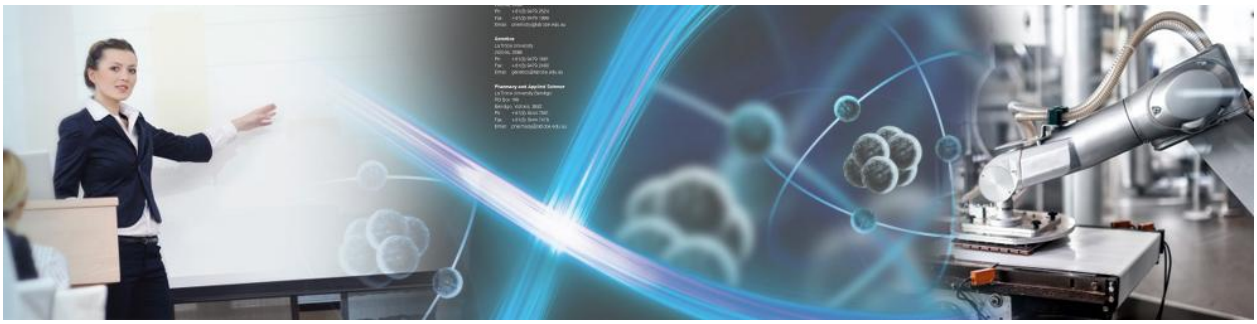
Міністерство освіти і науки України

Харківський національний університет радіоелектроніки

Кафедра комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії

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УДК: 005:004.896:62-65:338.3

Виробництво & Мехатронні Системи 2026: матеріали X-ої Міжнародної конференції, Харків, 22-23 жовтня 2026 р.: тези доповідей / [редкол. І.Ш. Невлюдов (відповідальний редактор)].-Харків: [електронний друк], 2026. – 87 с.

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Редакційна колегія: І.Ш. Невлюдов, В.В. Євсєєв.

Manufacturing & Mechatronic Systems 2026: Proceedings of X st International Conference, Kharkiv, October 22-23, 2026: Thesises of Reports / [Ed. I.Sh. Nevlyudov (chief editor).] .- Kharkiv .: [electronic version], 2026. - 87 p.

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Міністерство освіти і науки України (МОНУ)
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МАТЕРІАЛИ

X-ої Міжнародної Конференції

ВИРОБНИЦТВО
&
МЕХАТРОННІ СИСТЕМИ 2026

(22-23 жовтня 2026)
Харків, Україна

Ярослав Бєлий, Дмитро Гурін

Аналіз принципів нульової довіри для побудови кіберфізичної системи віддаленого моніторингу та керування промисловим обладнанням …… 49

Olha Shevchenko, Svetlana Sotnik

Comparison of Simulation Environments: Wokwi, Tinkercad, Falstad Circuit Simulator …… 53

Vladyslav Yevsieiv, Kyrylo Luchaninov

EDGE Method for Identification and Prediction of Dynamic Object Trajectories for a Mobile Robot Based on YOLO26n …….. 57

Ростислав Колногузов, Дмитро Гурін

Розроблення автоматизованого модуля орієнтації сонячної панелі з адаптивним керуванням за метеорологічними параметрами …….. 61

Михайло Лазаренко

Структура системи автоматизованого керування автоматичною насосною пневматичною установкою …… 64

Tymofii Cherednichenko, Svetlana Sotnik

Typology of a Mobile Robot's Internal Data and the Threats to Their Security 68

М. С. Черкашин, С. В. Хрустальова

Сучасні підсистеми автоматизованого обліку робочого часу операторів сортувальних ліній на основі RFID-карт …… 73

Artem Shevchenko, Svetlana Sotnik

Review of Methods for Ensuring the Positioning Accuracy of an Industrial Robot During Technological Operations …… 75

Vladyslav Yevsieiv, Svitlana Starikova

Analysis of the Effectiveness of Using a Mobile Robot Digital Twin for Teaching School Students the Fundamentals of Robotics …….. 80

Oleksandr Kolbasa, Svetlana Sotnik

Sensors and Navigation for Energy-Efficient Mobile Robots …… 83

Review of Methods for Ensuring the Positioning Accuracy of an Industrial Robot During Technological Operations

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Annotation: The work considers the causes of deviation of the working body of an industrial robot from a specified position and trajectory during welding, drilling, assembly, and machining. In the course of the analysis, positioning accuracy, repeatability, and trajectory reproduction accuracy were distinguished. Calibration of the kinematic model, deformation compensation, motion profile correction, and the use of technical vision and force feedback were analyzed. It was determined that the choice of method depends on the source of the error, the nature of the load, and the requirements of the operation. A verification sequence was proposed that begins with checking the basing and coordinate systems and ends with checking the result at independent positions and by the quality of the finished part.

Key words: industrial robot, positioning accuracy, repeatability, calibration, machine vision, motion profile correction.

I. INTRODUCTION

The development of robotics and manufacturing automation has made industrial robots a common means of performing welding, assembly, and machining operations [1-9]. As product quality requirements grow, the robot's role increasingly shifts away from simply moving objects toward performing operations with tight tolerances on the result.

During welding, drilling, or assembly, the robot must move the tool to a specified position relative to the workpiece. Even when the drives accurately reproduce the controller's commands, the actual tool action point may not coincide with the calculated one. The consequences include seam displacement, hole positioning error, a poor joint, or additional loads during assembly.

The accuracy of an operation is determined by the entire technological system: the robot mechanism, the gripper or tool, the fixture for securing the workpiece, the coordinate system, the sensors, and the control algorithm [10-19]. An error in any of these elements translates into an error in the relative position of the tool and the workpiece. Therefore, assessing only the manipulator's repeatability data is insufficient.

Despite a considerable number of publications on individual methods for correcting positioning errors of industrial robots, a number of issues remain insufficiently studied [20-24]. In particular, positioning accuracy, repeatability, and trajectory reproduction accuracy are not always distinguished, although they describe different properties of the system. Little attention is paid to identifying the source of the error (systematic bias or variable scatter) before choosing a method to eliminate it. Calibration methods, deformation compensation, motion profile correction, technical vision, and force feedback are usually considered separately, without comparing their application limits under different loads, speeds, and types of operation. The procedure for verifying the result also remains insufficiently defined: it is often performed at the same positions used to set up the system, rather than at independent positions and based on the quality of the finished part.

Thus, the relevance of this work stems from the need for a well-grounded choice of accuracy improvement method depending on the error source, loading conditions, and requirements of a specific technological operation, as well as the need for a unified verification sequence that allows assessing the actual result rather than only the manipulator's indicators.

The aim of this work is to analyze and compare methods for ensuring the positioning accuracy of an industrial robot and to determine the conditions for their expedient application when performing various technological operations. The analysis covers systematic and variable errors and methods for their measurement and correction; quantitative results for a specific robot model are not claimed here.

II. ACCURACY INDICATORS AND SOURCES OF ERRORS

The position of the end effector is specified by the coordinates and orientation of the system associated with the tool. The tool center point, or TCP (tool center point), must be defined precisely at the point where the operation is performed. Positioning error characterizes the deviation of the actual pose from the specified one, while repeatability characterizes the scatter of results when repeatedly returning to the same command under identical conditions. A robot may consistently arrive at a single point that is simultaneously displaced from the required one.

For motion along a seam or contour, trajectory error is also important: the distance between the actual and specified line at each moment of the operation. Evaluating only the endpoint will not reveal a deviation in the middle of the path. Tool orientation must be monitored separately: at a large distance from the flange to the TCP, a small angular displacement produces a noticeable linear displacement of the working point.

An arbitrarily chosen sensor is insufficient for measuring pose. The measuring device's coordinate system must be referenced to the workpiece, and its own uncertainty must be smaller than the permissible error of the operation. A device that measures only the coordinates of a single point does not provide complete information about

tool orientation. If the direction of the drill or torch axis is critical, monitoring of angles or several points on the tool is also required.

Comparison of the specified and measured poses must be performed in a single coordinate system and under identical loading conditions. If the workpiece coordinate system is defined incorrectly, even a properly calibrated robot will execute the command relative to a false zero. Errors also arise when the tool is changed, the workpiece fixture is loosened, or the TCP is specified incorrectly.

Geometric sources include inaccurate link dimensions, displacements of axis zero positions, and errors in the relative arrangement of the robot base, camera, and workpiece. Mechanical causes encompass elastic deflection of links and transmissions, backlash, and changes in geometry during heating. The degree of their influence depends on the manipulator configuration, tool mass, and cutting or clamping force.

To establish the nature of the deviation, the mean position after several approaches to the point and the scatter of individual measurements are compared. A stable displacement can be accounted for by a correction to the model or to the workpiece coordinates; an unstable scatter requires identifying the causes in the mechanics, workpiece gripping, sensors, and process conditions. Testing at several regions of the workspace shows whether a single local correction is sufficient.

The dynamic component grows with speed and acceleration when the drives and structure are unable to reproduce the specified motion without deviation. Vibration, measurement delay, and changes in workpiece position during the cycle also affect the result. Therefore, tests should be conducted at the working speed, with the required tool and typical load, and not merely in one convenient reference pose.

III. METHODS FOR ENSURING ACCURACY

Geometric calibration begins with measuring the robot's actual poses in different regions of the workspace. Using these data, the parameters of the kinematic model are refined: zero offsets of the axes, link parameters, and coordinate transformations between the robot base and the external system. The TCP and the workpiece coordinate system are calibrated separately. Measurements can be performed with an external coordinate measuring device; the data used for verification should be separated from the data used to estimate the parameters.

Calibration mainly reduces constant model deviations. If the error changes significantly with a different workpiece mass, temperature, or speed, a single geometric correction is insufficient. For such conditions, compensation of elastic deformations under load, temperature corrections, and error maps in the workspace are applied. The parameters of these models must be verified across the range of poses and loads in which the operation will be performed.

For a stable task with unchanging tooling, local teaching of the trajectory on the actual workpiece is useful. The operator refines the reference points, after which the robot repeats the verified path. This method is fast for an individual operation, but readjusting the gripper or displacing the workpiece may require retraining. It does not provide grounds to assume that the entire robot workspace has become accurate.

After replacing the tool, repairing an axis, or changing the robot's mounting, the reference poses are checked again. Restoring a saved program returns the commands but does not restore the physical geometry of the installation. For serial production, it is convenient to fix several reference poses near the working zone and compare their measured coordinates with the initial state before starting a batch.

Technical vision measures the position of the workpiece, edge, or seam and transmits a correction to the control system. Before the cycle begins, the camera can update the workpiece coordinates; during motion, it can refine the trajectory if the controller and processing algorithm provide sufficient speed. In both cases, calibration of the relationship between the camera and the robot, verification of image quality, and assessment of delay are required. In the absence of visible features or when the view is obstructed, such a measurement channel does not work reliably.

The camera can be mounted stationary relative to the workstation or installed on the manipulator. The first scheme simplifies viewing the entire zone if the workpiece is continuously visible. The second allows the camera to be brought closer to the object but adds the need to precisely determine its position relative to the flange. With continuous correction, it is important to match the moment the image is captured with the current robot pose: a correction based on an outdated frame may shift the tool in the wrong direction.

When the tool contacts the surface, a force and torque sensor enables correction of the clamping force or direction of motion. This is useful for grinding, polishing, and assembly with fitting. The force signal indicates the nature of the contact but by itself does not establish the absolute position of the workpiece in space.

Motion profile correction involves reducing speed in sections with sharp changes in direction, a smooth acceleration profile, and correct specification of the tool mass and its center-of-mass position, which reduces the dynamic component of the error. However, reducing speed increases the cycle time. The motion mode must be set according to the quality requirements of the specific operation and verified on the actual trajectory. The conditions for applying the methods are summarized in Table 1.

Table 1. Use of error correction methods

Method	What it adjusts and under what conditions
1	2
Geometric calibration	Systematic error of the model and coordinate systems. Requires external measurements and verification at independent poses.
Compensation of deformations	Deflection of the structure under the action of tool mass and working forces. Acts within the verified loads and positions.

Continuation of table 1

1	2
Technical vision	Displacement of the workpiece and local deviation of the seam or contour. Requires calibration of the camera, lighting, and consideration of delay.
Force feedback	Deviation during contact and fluctuation of force. Requires sensitivity adjustment and does not determine absolute coordinates without another measurement.
Motion profile correction	Dynamic component of the error at high speeds and accelerations. Requires verification on the actual trajectory and at working speed.

IV. CONSTRUCTION AND TESTING OF THE CORRECTION SYSTEM

The choice of method begins with the tolerance on the result of the operation. For drilling, this is the position and orientation of the hole axis; for welding, it is the deviation of the tool from the joint and the permissible change in speed along the seam. Next, it is determined what exactly needs to be measured: the TCP pose in the workpiece coordinate system, the deviation from the trajectory, or the interaction force.

The instrument and the measurement procedure must be sufficiently accurate to verify the established tolerance.

During planning, the margin between the tolerance on the finished part and the total error of the installation is taken into account. The robot's contribution cannot be assessed separately from the error of workpiece locating, tool setup, and measurement.

If almost the entire tolerance has already been consumed by fixture displacement, more precise actuation of the drives will not ensure the suitability of the part. Therefore, the verification sequence begins with locating and coordinate systems, after which the robot model and motion control are evaluated.

The verification sequence is shown in Fig. 1.

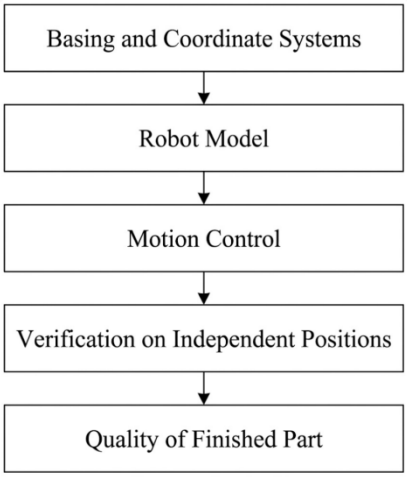


Fig. 1. Sequence of checking the correction system

The method also depends on when the object changes. If all workpieces are installed in a fixture with identical geometry, a fixed program may suffice after calibration and verification. If the position of each part differs slightly, the coordinate system is refined before the operation using measured features. When the edge or seam itself deviates within the part, the trajectory is corrected section by section, rather than only by a single initial offset.

Measurement at several positions and with repeated approaches allows distinguishing a steady displacement from random scatter. If the displacement repeats, the TCP, the workpiece coordinate system, and the kinematic model are checked. If the magnitude of the error changes with pose or load, deflection and temperature conditions are investigated. If the deviation appears only during fast motion, the motion profile is corrected and the trajectory is verified during execution.

For welding a seam on a part of variable shape, it is advisable to first determine the workpiece position and then refine the path along the edge. For drilling in a rigidly fixed part, priority is given to precise alignment of coordinate systems, the TCP, and spindle orientation; a camera that locates only the center of the part will not verify the drill's tilt angle.

During grinding, the clamping force should be controlled during motion, but the initial trajectory must still be specified in the coordinates of the surface being machined.

For assembling parts with a small clearance, a combination of two stages is useful: approaching the end effector using measured coordinates and careful correction during contact.

The first stage limits the initial displacement, while the second helps detect skewing or excessive force when inserting the part. Increasing force to overcome an unknown geometric error does not eliminate its cause and may damage the product.

For a part whose position changes from cycle to cycle, measurement before the operation or feedback during motion is introduced. The general sequence of actions is shown in Fig. 2. The command enters the correction model, the robot performs the motion, and external measurement provides data for the next correction. The update rate is selected according to the process speed and sensor delay.

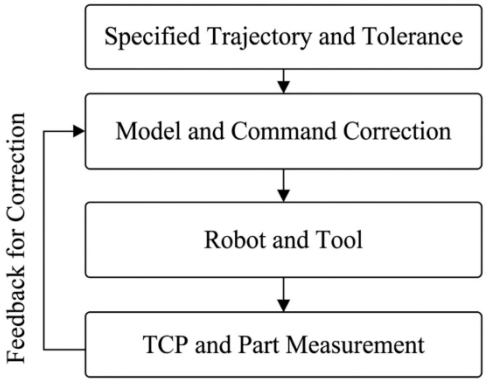


Fig. 2. Robot positioning correction scheme

After setup, the system is tested in positions that were not used during calibration, and measurements are repeated under the operating payload.

For trajectory operations, not only the average deviation but also the maximum deviation in critical sections is monitored.

The quality of the finished part is evaluated separately: tool coordinates serve as an intermediate indicator, whereas the final tolerance is set for the result of the technological operation.

The inspection protocol must record the target point, the measured TCP position, axis configuration, payload, speed, and part condition. Without these conditions, comparing two results becomes difficult.

During acceptance testing of the program, it is advisable to repeat the same control operations after the equipment has warmed up and, if necessary, at the end of the shift to detect drift. A change in results indicates which corrections require readjustment.

Positions approached by the robot from different directions should also be compared.

Differences in results may indicate backlash or structural deformation depending on the configuration. If a camera and an external measuring device yield different estimates for the same pose, their mutual calibration and measurement timing should be verified before applying a new correction to the program.

The correction scheme must provide limits for the allowable correction.

If the camera loses sight of the part or the force sensor outputs an inconsistent signal, motion based on unverified data may degrade accuracy.

In such a situation, the controller must halt the correction or switch to a predefined safe action in accordance with the specific setup parameters.

A correction obtained during the initial measurement of a part should not be added a second time within the current control loop.

Each channel requires a defined coordinate system and a rule for updating commands. This helps separate robot calibration from work-piece shift compensation and allows checking the residual error after their combined application.

In practice, a single method rarely covers all sources of error; thus, methods are combined based on suitability. Geometric calibration eliminates constant offsets in the model and coordinate systems, payload compensation and motion profile correction reduce regime-dependent components, while vision systems and force feedback address deviations that vary from cycle to cycle or arise during contact.

At the same time, each additional correction channel introduces its own error sources: measurement uncertainty, delay, and the risk of signal loss.

Therefore, channels should be introduced sequentially, with the residual error evaluated after each step rather than relying solely on the final operation result.

The boundaries of this review are determined by its target scope.

Qualitative criteria for method selection were considered, whereas quantitative accuracy metrics depend on the manipulator design, tool, and process conditions, and are thus omitted for specific robot models.

The tuning of correction algorithm parameters and the computational aspects of image processing were left outside the scope of this review. These matters may serve as topics for further research.

V. CONCLUSIONS

The positioning accuracy of an industrial robot depends on the alignment of the manipulator model, coordinate systems, mechanism condition, and technological process conditions. Repeatability demonstrates the stability of returning to a commanded position, but it does not confirm agreement with the target position; for contour motion, trajectory and tool orientation errors must be measured additionally.

Before selecting a method, it is necessary to determine whether the error is systematic or random by comparing the mean position and the variance of measurements. Geometric calibration is suitable for systematic errors, payload compensation for regime-dependent deformations, motion profile correction for errors occurring at high speeds, machine vision for variable part placement, and force feedback for contact operations. A sound choice is based on measuring the error under operating conditions. The proposed verification sequence includes checking part positioning and coordinate systems, evaluating the robot model and motion control, after which the result is validated at independent positions and by the quality of the finished part. If necessary, methods are combined by introducing correction channels sequentially and checking the residual error after each step.

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