Manipulator Motion Tracking Conceptual Model

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***Abstract*—The paper deals with the problem of low accuracy of movement of low-cost manipulators. A hardware-software conceptual model of the tracking system is proposed, which is based on four data sources: an accelerometer, a gyroscope, a laser range finder, and a video camera. An experimental prototype based on the proposed conceptual model has been developed. A digital model of a robotic arm was created. Also, a module that calculates the error of the movement of the manipulator was developed. Experiments were carried out to obtain an estimate of the accuracy of the manipulator movement according to two metrics: the angles between the links and the distance to the captured object.**

I. Introduction

The problem of errors in the manipulator operation has long been widely known [1]. The main problem is that due to inaccuracies in the operation of the manipulator, it is impossible to predict the result of its work. The unpredictability of manipulator work entails both economic and social risks [2]. For example, this can lead to injury to a person who was near the robot.

The first element of robot manipulator is a system of links connected by drives. This system is difficult both to manufacture and to operate. The sequential arrangement of the manipulator links leads to the fact that each link also bears the weight of the next segment. As a result, large bending moments act on each link. To take into account these forces, the requirements for rigidity are increased, which leads to an increase in mass. The second element of the manipulator is servos. The work of the servo is also affected by the weight of the structure that it moves. Thus, when moving, the manipulator is influenced by inertial forces, centrifugal forces, and Coriolis forces. All these factors complicate the control of the robot and affect the accuracy of its work.

Many studies have been devoted to this issue. Several approaches are used to solve the problem. The first group of approaches uses algorithmic methods that reduce the magnitude and number of errors by fine-tuning the control over the robot [3], [4]. That is, they solve the problem in advance, before it appeared.

Another group of approaches uses adaptive methods such as neural networks and reinforcement learning [5], [6]. This approach says: ”let the problem exist, we will gradually learn how to solve it”. In addition, increasing the accuracy of the manipulator is incorporated into the design of the manipulator itself [7], [8].

The purpose of this study is to develop the conceptual model of a system for recognizing the movement of a manipulator and estimating the magnitude of errors that occur during movement.

A software and hardware system is proposed which consists of a manipulator, its digital model, as well as a set of programs that connect them. The system simulates the movement of the virtual manipulator, which is the digital model of the real robot. Then it collects information about the movements of the real manipulator, and compares the positions of the virtual manipulator with the real one, calculating the values of the accuracy indicators.

The rest of the paper is organized as follows. Section II is devoted to an overview of existing approaches to solving the problem of recognizing deviations of manipulator links. Section III introduces the conceptual model of the proposed manipulator motion tracking system. Section IV presents the results of testing the system for two types of manipulators. Finally, Section V concludes the paper.

II. Related Work

Positional accuracy of an industrial robot is defined as the difference between the desired target position and the actual position reached by the robotic arm [9].

To measure the difference, you need to know the target position and the actual position of the manipulator. The algorithmic approach to controlling the manipulator is being worked out in virtual environments, such as MatLab [3], [4]. In a virtual environment, the target position is set by the researcher, and the real position is calculated from the simulation results. Thus, both positions are in the same modeling environment and their comparison is very easy. To work with a real manipulator, it is necessary to use additional tools with which you can determine the actual position of the manipulator. Such tools can be hand tools (such as a ruler) or sensors that collect information and transmit it to a computer for processing. In this case, the target position is specified separately, and in order to obtain the actual position, additional data processing must be performed, and only then it will be possible to calculate the position difference. To automate the process of measuring the accuracy of the manipulator, it is necessary to ensure the coordination of the input of the target position and the processing of sensor data.

A video camera can be used as one of the tools for determining the actual position of the manipulator [6], [10]. In [11] measurement of robot position accuracy is based on the coordinates of the robot base, which are constructed in the measurement software of the binocular vision measurement system.

In [12] the method to measure the positioning distance accuracy based on the multi-station technology of the laser tracer device is presented. With the help of the inductive

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sensors the geometric errors of industrial robotic manipulators measured in [13].

The sensors used to determine the actual position of the manipulator have their limitations in terms of measurement range, measurement accuracy, environmental conditions, size, installation options, and also differ in cost. For example, the video camera will not be able to get an image of an object if it is hidden from focus by another object, for example, by one of the links of the manipulator. The proposed calibration methods for a particular manipulator [9] are difficult to apply to other types of manipulators. For example, one of the conditions for applying the method is the continuous operation of the robotic arm for 30 minutes. For small robot arms, this mode of operation can lead to overheating, because their servos are not designed for such a load.

Recognition and tracking of a moving object in video can be implemented using a pan-tilt camera and a microcontroller [14].

Based on tracking the color palette and trigonometric transformations in the image applications can be implemented that detect the manipulation of the human hand [15]. For example, a human hand can be used as a doppelganger to a manipulator hand using machine vision algorithms.

In particular, a machine vision-based system is able to detect objects of a certain color and is able to determine their location in the robotś workspace [16], the position is determined by a value in the 3-axis plane, the color is determined in the RGB model using the red, green, blue values with the definition color threshold values.

The target position of the manipulator is either entered manually or calculated on the basis of theoretical models describing the movements of the manipulator. One of the approaches to describe the manipulator itself and its movements are digital twins.

ROS is a versatile and popular environment for robot simulation and control. ROS drivers have been developed for many types of robots. ROS can be used to configure the manipulator for motion planning [17], [18]. Also, for modeling and visualization of robots, researchers use specialized software Moveit, Gazebo, RViz visualization environment, CoppeliaSim [18], [19], [20]. This software allows to set and visualize the initial and final positions of the manipulator, as well as the entire trajectory of its movement, to find collisions or singularities at the stage of motion planning.

Thus, researchers use various approaches and tools to assess the accuracy of the manipulator. In each case, the researcher must choose the most effective approaches. To solve this problem, it is proposed to form such an conceptual model of the manipulator movement tracking system, which can be used for almost any manipulator.

III. Conceptual Model

The general scheme of operation of the manipulator movement tracking system consists of the following steps. A digital model of the manipulator is preliminarily created. It fully corresponds to a real manipulator in terms of dimensions, weight, degrees of freedom, ranges of movement of links, etc. The digital model is designed to control a real manipulator. For the digital model, the initial and final positions of the manipulator links are specified, and the trajectory of the manipulator movement from the initial position to the final position is simulated. Thus, the digital model serves as a target position for calculating the accuracy of the movements of the manipulator at any given time.

A hardware platform has been developed to determine the actual position of the manipulator. The platform includes a board for manipulator control. The board receives commands from the digital model. At the same time, the board interrogates the sensors that are installed on the manipulator. Sensors collect information about the state of the manipulator. The processing of this information makes it possible to obtain the actual position of the manipulator links. Next, the software module calculates the difference between the target and actual positions of the manipulator links.

The general algorithm of the architecture is described in Algorithm 1.

Algorithm 1 Algorithm of the architecture

1: In the digital model the movement of the links of the robot-manipulator is set;
2: The trajectory of the robot is calculated in a digital model;
3: Movement begins in the digital model;
4: The position coordinates of the links are transmitted to the synchronization module;
5: The synchronization module calculates commands for a real robot;
6: The synchronization module sends commands to the manipulator control module;
7: The manipulator control module sends commands to servo;
8: The manipulator control module sends commands to servo;
9: Manipulator control module sends requests to sensors;
10: Manipulator control module receives responds from sensors;
11: After executing the movement, the video camera fixes the location of the links and the capture of the manipulator;
12: On a laptop, video image processing is performed using the Video Image Capture and Processing Module, then the processing results are transferred to the Robot Manipulator Movement Accuracy Calculation Module;
13: Manipulator control module sends data to movement accuracy calculation module;
14: The synchronization module sends coordinates of the links of a digital model to the movement accuracy calculation module;
15: Movement accuracy calculation module evaluates motion accuracy;

Let's take a closer look at the hardware and software of the movement tracking system. The tracking system hardware consists of a laptop, single-board computer Raspberry Pi4, inertial sensors, sonars, a video camera, and additional boards. The names and purpose of the elements are described in more detail in the Table I.

The more degrees of freedom a robot manipulator has, the more sensors need to be installed on it. Each sensor has its own range of conditions within which it operates. The range finder (sonar) can measure distances no more than a given distance. The view (focus) of the video camera can be blocked by other parts of the robot, etc. Taking into account these points (features), the set of sensors may be redundant, but allowing in any position of the robot to obtain the information necessary for calculations from at least one sensor.

TABLE I. DESCRIPTION OF DEVICES

Device name	Purpose of the device
Laptop	Laptop acts as a host computer. It provides interaction with a single-board computer RaspberryPi4, performs processing of data coming from sensors, calculation of motion accuracy
IMU 10DoF (5 Items)	It provides accelerometer and gyroscope data about the position of a real robot
Module-based laser rangefinder VL53L0X (4 items)	It provides data on the distance to the object (links, the object of capture, etc.)
Single-board computer Raspberry Pi4	The single-board computer controls the robot's servos and collects data from the sensors
Servo control controller PCA9685	Sends control commands to servos
Multiplexer TCA9548A	Performs voltage level matching
Camera	It provides video data to determine the position of the robot

Commands for manipulator drive control are formed on the host computer to perform a useful action by the manipulator. The commands are generated by a digital model of the robotic arm. Feedback with the manipulator is carried out through sensors installed on the manipulator and an external video camera. A single-board computer provides interaction between the head computer and the sensors and servo drives of the manipulator. The single-board computer receives commands from the host computer and transmits sensor readings to the host computer.

Sensors (inertial sensors and distance sensors) are connected via a multiplexer to a Raspberry Pi4 single-board computer via an I2C interface. The servo control controller is connected via a multiplexer to a Raspberry Pi4 single-board computer via the I2C interface. The camcorder is connected to a laptop via a USB interface. The device interconnection diagram is shown in Fig. 1.

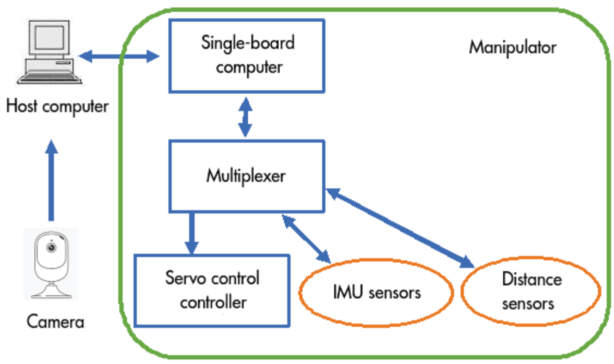


Fig. 1. Diagram of interconnections of architecture elements

The accuracy of the movement of the manipulator is determined by two metrics: the angle between the articulated links and the distance from the gripper to the captured object. The angle between the links can be determined based on the distance between the links or based on the coordinates of the links.

The distance can be determined based on the readings of the range finder. The coordinates of the manipulator links can be determined by processing the readings of the gyroscope and accelerometer. Based on the distance sensor, it is possible to determine the angle between the two links of the manipulator and the distance from the gripper to the gripped object. Recognition of the manipulator links on the video image will allow determining the coordinates of the manipulator links.

In order to determine the position of the robot links using a video camera, it is necessary to recognize the components of the robot in the image. This is a rather difficult task, the solution of which is specific for each type of robot. As a universal solution, special marks of a given size and color were used, which can be recognized in the image more easily than robot structural elements. The location of the marks on each link of the manipulator is fixed. Their relative position and rotation determine the position of the manipulator links.

The color of the marks is selected according to the color of the manipulator in such a way that a high contrast of the color of the marks against the background of the manipulator is obtained. This makes it easier to find and recognize mark boundaries using recognition algorithms. During measurements, it is desirable to use additional directional illumination to enhance the contrast of marks.

The tracking system software includes modules installed on a single board computer and modules running on a host computer. The software includes the following elements. The Ubuntu operating system is installed on the host computer, which ensures the operation of the developed modules and third-party software. The developed modules include Robot and Digital Model Synchronization Module, Video Image Capture and Processing Module, and Robotic Manipulator Movement Accuracy Calculation Module. External software includes Gazebo, MoveIt, Rviz, ROS. The Raspbian operating system is installed on a single-board computer, which ensures the operation of the developed Manipulator Control Module. The modules developed and the external software used are described in the Table II. The software interconnection diagram is shown in Fig. 2.

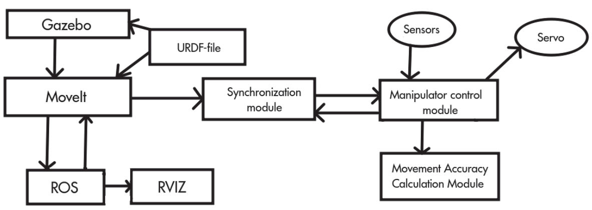


Fig. 2. Diagram of interconnections of software elements

To form the target position of the manipulator, its digital model is used. The main purpose of the digital model is to simulate the performance of some actions by a real robot and calculate the values of the sensor readings. The digital model corresponds to the main characteristics of the real prototype: the lengths of the links, their joints, the possible positions of the links, and the location of the sensors. The description of the digital model of the robot is presented in the Unified Robot Description Format (URDF), which is an XML-like language.

All of the used programs are distributed open source and with a free license, which allows adding your own functionality. Also, these tools are actively used in advanced developments [21]. For example, NASA is using ROS to test the behavior of lunar rovers, and Boston Dynamics is training humanoid robots in Gazebo. Another important advantage is the fact that these software tools are used by a large number of researchers and engineers, which made it possible to form a community of enthusiasts who constantly refine the software product, write documentation, and develop training courses. All of the above suggests that software tools such as ROS and Gazebo will continue to gain their popularity, which means that their use in research and development has great prospects.

The architecture of the system provides sets of different types of sensors, the readings of which make it possible to calculate various indicators of the accuracy of the movements of the robot manipulator. In some cases (for some positions of the robot manipulator links), it will be possible to obtain the information necessary for calculations from only one sensor, for example, from a distance sensor (sonar) or a gyroscope. In other cases, the indicators can be calculated based on the values received from several sensors, for example, from a gyroscope and a video camera. It may turn out that the calculated values of the same indicator according to the readings of different sensors will differ from each other. In this case, the problem arises in choosing the most reliable value.

Any sensor is affected by various random factors that can lead to noise in the sensor readings or even to the failure of the sensor readings. Therefore, the processing of the readings of each sensor begins with calibration. The readings are then filtered to eliminate noise. At the last stage, an analysis is carried out to identify anomalies in the sensor readings [1-3]. The cleaned and verified sensor readings can be used to calculate the accuracy of the movements of the robot.

If it turns out that it is possible to use the readings of two sensors to calculate some indicator, then the sensor whose readings have passed the verification procedure is selected. If the readings of both sensors have passed the verification procedure, then the calculations of the indicator are averaged according to the readings of both sensors. If there is additional information about the reliability of the readings of each sensor, then if the reliability of one of the sensors is below the specified limit, then its readings are discarded.

The main advantage of the proposed architecture is its modular nature. In the event that one of the modules fails, it can be replaced by another of the same module, without the need for a complete replacement of the entire complex. This allows you to ensure the reliable operation of the system. Hardware modules were selected based on low cost and availability. It should also be noted that all modules are quite simple in their design and operation.

However, the relative simplicity of the software and hardware complex has certain disadvantages. Installing sensors directly on the body of the manipulator leads to the appearance of additional noise in the readings of the sensors due to natural vibrations of the manipulator caused by the operation of the drives and the movement of the manipulator links. To extinguish these noises, it is necessary to use special fasteners made of noise-absorbing materials and of an appropriate design.

IV. Experiments

A. Hypotheses

Several hypotheses were put forward for the developed manipulator motion tracking system.

1) Deviations of the position of a real robot from the position of a digital model can be recognized using inertial sensors, distance sensors, and video data.
   This statement means that due to the incomplete match between the digital model and the real robot, deviations in positions will be observed. To assess the accuracy of the movement of the manipulator, it is necessary to recognize these deviations. The ability to recognize the deviation is tested in the course of experiment No. 1.
2) a) Based on the readings of the inertial sensor, it is possible to calculate the angles between the links of the manipulator.
      Since the position of the links can be determined using generalized coordinates, these coordinates can be obtained using inertial sensors. The possibility of obtaining generalized coordinates based on data from IMU sensors is tested during experiment No. 1
   b) Based on the readings of the inertial sensor, it is possible to calculate the coordinates of the capture.
      If hypothesis 2a is true and generalized coordinates can be obtained, then Cartesian coordinates can also be obtained based on generalized coordinates. The possibility of obtaining Cartesian coordinates of the capture is checked during experiment No. 1
   c) Based on the readings of the distance sensor, one can calculate the distance to the capture object.
      The hypothesis assumes that the captured object (in a given hardware architecture) will fall within the range of the distance sensor. The hypothesis is tested during experiment No. 2
3) Deviations of the positions of a real robot from a digital model can be fixed based on the correctness of hypothesis 2a.
   The hypothesis is tested during experiments No. 1 and No. 2
4) Based on the correctness of hypothesis 2c, it can be judged that the object is captured.
   The hypothesis is tested during experiment No. 2
5) Based on the correctness of hypothesis 2c, it is possible to fix the moment when the manipulator drops the object.
   The hypothesis is tested during experiment No. 3.

TABLE II. DESCRIPTION OF SOFTWARE

Name	Purpose	Input data	Output data
Operating System Ubuntu 20.04	For host computer	–	–
Operating System Raspbian	For RaspberryPi	–	–
File URDF of the description of the digital model	This is used to simulate the movements of the manipulator and obtain the target values for angles, coordinates, and distances	–	–
Robot Operating System (ROS)	This is used to perform actions in the simulation and transfer the coordinates of individual links, grabs, and other objects	URDF file describing the digital model	–
Gazebo	This implements interactions with the capture object	URDF file describing the digital model	–
MoveIt	It performs the calculation of the trajectory of the movement of the manipulator, implements the movements in the simulation	–	Angles of the robot_arm and robot_hand link groups of the robot arm in the simulation
Rviz	This performs visualization of the trajectory of movements and the movements themselves	–	–
Manipulator control module for Raspberry Pi	It implements the transmission of commands to servos, the collection of data from sensors, the transmission of data to the module that analyzes the accuracy	Servo numbers and their positions	Sensors data
Robot and Digital Model Synchronization Module	Synchronizes the position of a real robot with a digital model	Link numbers and angles between them in simulation	Numbers of links and the values of the corresponding angles
Video capture and processing module	Performs video capture and processing	Video from camera	Recognized image with green labels with the following data: numbering, area, angle of rotation
Module for calculating the accuracy of the movement of the robot-manipulator	Calculates the accuracy of the movement of the manipulator	Sensor data and position data from simulation	Evaluation of the accuracy of the movement of the manipulator

B. An experimental prototype

To test the hypotheses, it was necessary to build an experimental prototype. The prototype consists of the main components of the conceptual model described above. Robots from ABB Industrial and Dobot Magician robots were used as robotic arms. It should also be noted that the partial operation of the hardware-software complex is possible in the absence of any real robot. Simulating movement in a digital model helps in many ways to predict the behavior of a real robot.

Robots from ABB Industrial include seven links. Link1 is responsible for rotating the base of the manipulator around its axis. Link 2 is connected to the base and forms a large lever. Link3 is connected to Link2 and forms a small lever. Link4 is responsible for turning the gripper left/right. Link5 raises or lowers the gripper. Links 6 and 7 form the gripper.

The experimental prototype is shown in Fig. 3. The prototype includes the robot itself and its digital model, which is visible on the monitor. With the help of a digital model, the movements of the manipulator links are planned. These movements are displayed on the monitor. The digital model, performing the movement, transmits the appropriate command to the real robot, which must repeat these movements. According to the readings of the sensors installed on each link of the manipulator, the accuracy of the movements of the manipulator is determined.

C. Experimental setup

Three experiments were carried out with the ABB Industrial Robot: manipulator control, object capture, object capture, and manipulation.

In experiment No. 1, commands were executed to change the position of each link of the manipulator separately. This allows you to determine the accuracy of each servomotor of the manipulator. It should be noted that the position of the fixed links affects the accuracy of the movement of the movable link, as it changes the coordinates of the center of mass, and, as a result, changes the weight being moved.

In experiment No. 2, commands were executed that changed the positions of two gripper links simultaneously. Thus, the operation of one servomotor could affect the operation of another servomotor. In experiment No. 3, all links of the manipulator were involved. The manipulator had to perform useful work, namely, to capture the object and move it to another place. This experiment is aimed at determining the accuracy of the operation of the manipulator as a whole. Description of experiment No. 2 is presented in the Table III.

In experiment No. 3, video data analysis was used. Determining the position of the links of the manipulator is based on the recognition of special marks installed on the manipulator. The mutual arrangement of the marks, their rotation relative to the initial position allows us to calculate the angles between the links of the manipulator. Green rectangles (adhesive plastic bookmarks) 12x45mm in size are used as labels. Example is shown in Fig. 4.

The label recognition program is written in the Python programming language on Ubuntu 20.04. We used the OpenCV, NumPy libraries, and the findContours, minAreaRect, drawContours functions to find contours, calculate their areas and draw them, respectively. Experiments with video data were carried out on a server computer: Intel Core i9-9900K CPU, 32GB RAM, GeForce RTX 2080 8GB GPU.

The accuracy of experiments with video data was determined as follows: the value of the real angle between the mark located on the part of the manipulator in a certain position and the value of the angle recognized by the module was measured. To test experiments with video data, marks were manually selected into rectangles, and then the resulting difference in

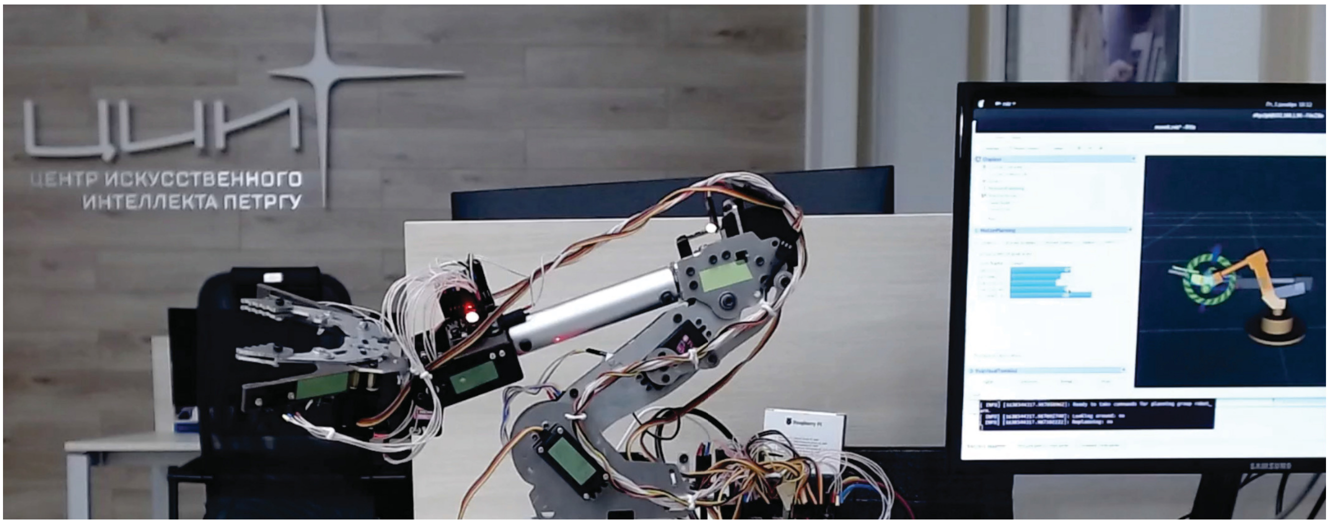


Fig. 3. The experimental prototype with Robots from ABB Industrial

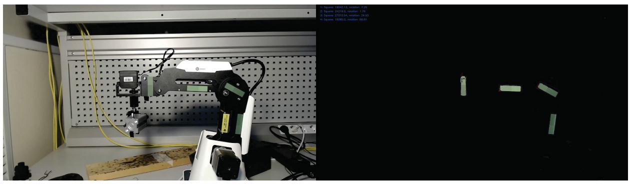


Fig. 4. Angles recognition on the manipulator with green labels

angles between the values obtained manually and recognized by the algorithms was compared.

Description of experiment No. 3 is presented in the Table IV. In the column ”Position number” first digit is a state of manipulator, second digit is a number of the mark whose position is recognized.

Due to the certain color of some parts of the Dobot Magician robot, it was possible to place the marks in the most accurate and most easily verified method. The color of the manipulator links is mainly represented by black (neutral) color, which enhances the contrast of the green color, which makes it easier to find these marks using recognition algorithms. Among other things, objects with bright (white) or similar (green) backlighting were excluded from the experiment, for example, bright inscriptions from the monitor image, green keyboard backlight, etc. Moreover, some of the experiments were carried out using additional directional illumination (light from a lamp) to enhance the contrast of the marks. The marks were successfully recognized, including different positions of the manipulator links.

D. Results of experiments

Experiments with the ABB Industrial Robot showed low accuracy in performing movements. In this case, 2 cases of operation of the experimental prototype were identified. In the first case, the robot followed commands, doing it inaccurately, but without performing unauthorized movements. In the second case, the robot performed the necessary actions, but at the same time performed additional movements that were not programmed.

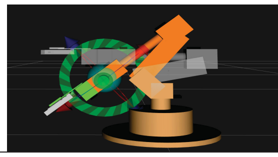
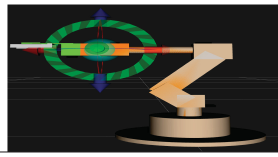
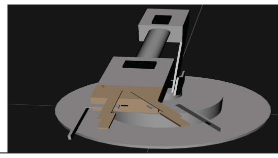
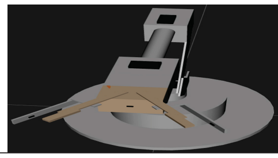
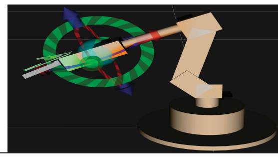
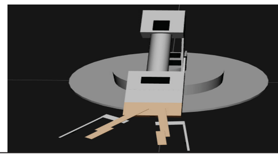
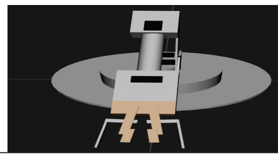
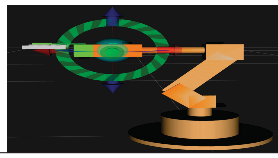
Unauthorized actions manifest themselves as follows: at an arbitrary moment in time, an arbitrary link can start moving and continue moving from corner A to corner B and back until the program stops. This phenomenon was especially pronounced in experiment No. 3. However, this anomaly contributed to the confirmation of the hypotheses stated before the experiments: the readings of the sensors stably recorded such activity. This fact suggests that such anomalies can be detected based on the readings of the sensors.

The reasons for this behavior of the manipulator may be errors in the code of functions taken from third-party libraries of the servo controller driver, incorrect operation of the power supply, incorrect electrical circuit in the motor control board, low-quality elements inside the servos. In the first case, the deviation of the position of the links relative to each other, based on information from the sensors, ranges from 3 to 15 degrees. This result was obtained during the experiment No. 1. In the second case, the deviation of the position of the links relative to each other can reach 50 degrees. If such a deviation occurs, it can be argued that an unauthorized movement has occurred. During experiment No. 2, the object was successfully captured in cases where there were no unauthorized actions described higher.

High deviations are due to the fact that the drives used in the robot initially had a low rotation accuracy. The placement of additional equipment on the robot links led to an increase in the weight of each link, which in turn reduced the power of the drives and, as a result, the accuracy of their work. At the same time, this did not affect the conceptual basis of the system.

Experiments conducted with the Dobot Magician robot use a video camera. Experiments have shown the accuracy of determining the angles between the links of the manipulator with an error of no more than 7 degrees. On average, the deviation was about 3–4 degrees.

TABLE III. DESCRIPTION OF THE EXPERIMENT NO 2. CAPTURE OF AN OBJECT

Position	**Initial state (degrees)**	**Final state (degrees)**	**Picture**
1 – Initial state of the manipulator	Link2 = 0	Link2 = -40	
2 – Preparing the manipulator for the task	Link3 = 0	Link3 = 40	
3 – Gripper disclosure	Link6 = 0	Link6 = 30	
4 – Gripper disclosure	Link7 = 0	Link7 = -30	
5 – Bringing the gripper to an object	Link2 = -40	Link2 = -65	
6 – Gripper closure	Link6 = 30	Link6 = 5	
7 – Gripper closure	Link7 = -30	Link7 = -5	
8 – Moving	Link2 = -65	Link2 = -40	

The experiments carried out confirmed all the hypotheses put forward. The readings of the sensors make it possible to calculate the accuracy metrics of the manipulator and determine the success of the work assigned to it.

E. Discussion

The use of a digital model frees from additional laborious calculations to determine the reference position of the manipulator links. Despite the fact that the digital model must exactly match the simulated robot, its description is unified. Ready-made models are available for various robots that are easy to integrate into the proposed system. Another advantage of the proposed conceptual model is the inclusion of several types of sensors in its structure. A variety of sensors for determining the actual position of the manipulator links makes it possible to use the system in a different environment, as well as to verify the readings of some sensors based on the readings of other sensors. The system is scalable both in terms of the number of sensors used and in terms of their types. The conceptual model of the system allows to the addition of any new type of sensors.

The conceptual model of the system as a whole implements

TABLE IV. DESCRIPTION OF THE EXPERIMENT NO 3. DETERMINING THE POSITION OF THE LINKS ON THE MANIPULATOR

Position number	Recieved angle value	Deviation of the angle value
1.1	7.07	2-3
1.2	89.18	4-5
1.3	22.93	6-7
1.4	90	0-1
2.1	90	0-1
2.2	6.74	1-2
2.3	49.44	2-4
2.4	20.12	4-5
3.1	3.7	6-7
3.2	24.75	5-6
3.3	7.13	2-3
3.4	86.72	3-4
4.1	48.89	1-2
4.2	1.47	1-2
4.3	67.96	5-6
4.4	90	0-1
5.1	7.81	1-2
5.2	1.6	1-2
5.3	26.57	3-6
5.4	90	0-1

the feedback of a digital model with a real manipulator, which can be used for the subsequent implementation of adaptive control of the manipulator in order to increase the accuracy of its operation.

The calculated indicators of the accuracy of the operation of the manipulator make it possible to evaluate the accuracy of both individual elements of the manipulator and the operation of the manipulator as a whole.

Approbation of experimental prototypes showed the need to use vibration-absorbing sensor mounts to the manipulator to eliminate the influence of external noise on the sensor readings. Algorithms for processing sensor readings, including video image processing, must be accurate enough to correctly determine the accuracy of the movement of the manipulator.

V. CONCLUSION

The paper presents the conceptual model of the manipulator movement tracking system. The conceptual model of the system is based on a modular principle, which allows varying hardware sets and software modules to control the manipulator. The proposed conceptual model is universal and can be used for a large number of different manipulators. The external software used is open-licensed and is constantly being improved. The conceptual model of the system includes a digital model of a robotic arm, which makes it possible to generate tasks for a real manipulator, transmit commands to it and demonstrate the operation of a manipulator in simulation mode, including in the absence of some of the necessary equipment. Experiments have shown that the model is viable and can be used to determine the accuracy of the manipulator.

Further development of the system is planned in the direction of expanding the types of assessment of the quality of movement, for example, determining the delicacy of the grip, the reliability of the grip. In addition, it is of interest to assess the accuracy of the trajectory of the movement of the manipulator, the smoothness and uniformity of movements, the preservation of the position of the object when moving the object, for example, the elimination of liquid spills when transferring a filled glass. All these characteristics are characteristic of a person when performing actions (manipulations with objects) with the help of a hand and are qualitative characteristics of the movement.

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