Development of automated accuracy control tools for robotic equipment

A A Potapov, A A Fedorov, V M Masyuk and S Y Orekhov

Kaluga Branch of Bauman Moscow State Technical University, Russia, 248004, Kaluga, Bazhenova st., 4

andrewpotapov@yandex.ru

Abstract. This paper proposes a new method of visual automated control based on optical measurements. In this article, we investigate a number of questions concerning the organization of measurements, calibration of the data obtained, and interpretation of results. An experimental scheme is given, the coordinates of the gripper of a robotic manipulator are obtained by different methods, the accuracy is estimated. It is concluded that the use of the proposed method based on visual markers for obtaining coordinates based on visual markers has high accuracy, good repeatability of results and can be used to control the positioning of new robotic mechanisms at the testing and commissioning stage.

1. Introduction
Currently, the problem of the accuracy of robotic equipment is particularly relevant and the introduction of tools that use visual automated control can become an integral part of any robotic production, and with the necessary accuracy of the means used, can become the main accuracy control system. At this stage, in the way of the implementation of this technology, there is the inaccuracy of tools that use computer-aided visual control. The first step in solving this problem is to estimate the errors in determining the coordinates of the gripper of an industrial robot using the method of visual automated control. Using a more accurate method - a direct method, it is possible to determine the error of the results obtained by the method of visual automated control. By the direct method, we mean the coordinates of the gripper [1], obtained as a result of software testing of a fully intact calibrated industrial robot. To determine the accuracy of the results, it is necessary to compare the coordinates of the gripper of an industrial robot obtained by the direct method and by the method of visual inspection [2] when moving the gripper in preset positions.

For carrying out this experiment, evaluation of the methodology and calibration of further results, the industrial robot FANUC R-2000iB was used, at the end of the gripper of which the LED was fixed. A script was originally developed for the robot, as a result of which the gripper of the manipulator moves between 3 points in space along a predetermined path. During the execution of the program, a video fixation of this experiment was carried out, the data in the form of freeze frames were transmitted to a PC, then using the Matlab program, the coordinates of the LED were obtained from the received fragments. At this stage, three frames were considered, from which coordinates were obtained and compared with the data on the position of the LED relative to the program-specified ones.
Of all the projections employed in computer graphics, the perspective projection is one most widely used [3,6]. There are two stages to its computation: the first involves converting world coordinates to the camera’s frame of reference, and the second transforms camera coordinates to the projection plane coordinates. Now we investigate how camera coordinates are transformed into a perspective projection. We begin by assuming that the camera is directed along the z-axis as shown in figure 1. Positioned d units along the z-axis is a projection screen, which is used to capture a perspective projection of an object. Figure 2 shows that any point \((c_x, c_y, c_z)\) is transformed to \((p_x, p_y, d)\). It also shows that the screen's x-axis is pointing in the opposite direction to the camera's x-axis, which can be compensated for by reversing the sign of \(p_x\) when it is computed. Figure 3 shows a plan view of the scenario depicted in figures 1, and 2 a side view. Next, we reverse the sign of \(p_x\) and state:

![Figure 1. The axial system used to produce a perspective view.](image1)

![Figure 2. The plan view of the camera’s axial system.](image2)
This is expressed in matrix form as:

$$
\begin{bmatrix}
    x_p \\
    y_p \\
    z_p \\
    w
\end{bmatrix} = \begin{bmatrix}
    -1 & 0 & 0 & 0 \\
    0 & 1 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 1/d & 1
\end{bmatrix} \begin{bmatrix}
    x_c \\
    y_c \\
    z_c
\end{bmatrix}
$$

What can be represented as:

$$
[x_p, y_p, z_p, w]^T = [x_c, y_c, z_c, w/d]^T
$$

and if we remember the idea behind homogeneous coordinates, we must divide the terms $(x_c, y_c, z_c)$ by $w$ to get the scaled terms, which produces

$$
\begin{align*}
x_p &= \frac{-x_c}{z_c/d} \\
y_p &= \frac{-y_c}{z_c/d} \\
z_p &= \frac{-z_c}{z_c/d}
\end{align*}
$$

2. Experiment

The first step in the experiment was the creation of coordinate systems for an industrial robot: Tool frame and User frame. The mapping of coordinate systems is presented in figure 4.

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**Figure 3** - The side view of the camera’s axial system.
The second step was the creation of a program for the FanucR-2000B 210F robot, which sets the movement of the LED along three points of the trajectory. The program code is presented in figure 5.

![Figure 5. Program code.](image)

According to the results of this program, the coordinates of three points were obtained, between which the LED moved linearly, table 1.

![Table 1. Coordinates of points obtained by the direct method.](image)

The third step was to determine the coordinates of the three positions of the LED using the proposed method. The coordinates of the position of the gripper of an industrial robot in space are determined using the Matlab program, by using the Prewitt method.

To determine the position, we give the following algorithm of actions:
1. For the purpose of non-interference in the operation of equipment, we use a transparent panel.
2. We install the camera and adjust it relative to the panel.
3. We measure and set the working area of the system.
4. For 3 given points, we obtain the necessary calculated relations. The next step is the calculation of the positioning error. At this stage of the research, one camera was used to obtain results in one plane to verify the method. The result of this program was the recognition of the LED on the image presented in figure 6.

![Image](image.png)

**Figure 6.** View of the work program window after the recognition of the light marker.

After conducting a mathematical calculation [4], the coordinates of three points were obtained using the method of visual automated control, table 2.

| Point (position) | X, мм  | Y, мм  |
|------------------|--------|--------|
| 1                | 312.268| 346.754|
| 2                | 156.770| 615.542|
| 3                | 330.148| 835.49 |

Comparing the experimental results obtained by the direct method and the method of visual automated control, one can obtain the error of the developed method of visual automated control on the X-axis equal to $\Delta = 1.4$ mm and on the Y-axis equal to $\Delta = 1.7$ mm.

For the experiment, a camera with the following characteristics was used: Sensor model: Samsung S5K3P8 [5]; Sensor size: $4.74 \times 3.56 \text{мм}^2$; 4608x3456 (15.93 Mп)

Photo accuracy with regard to the quality factor (optical resolution, diffraction, etc.); $k = 0.4 \div 0.5$; $l = 1600 \text{мм} / 4608 \approx 0.35 \text{мм} / l / k = 0.875 \text{мм}$ In the video mode, taking into account the quality factor (the resolution of the optics, diffraction, etc.); $k = 0.8$; $l = 1600 \text{мм} / 4608 \approx 0.35 \text{мм} / l / k = 0.4375 \text{мм}$. 
The positioning accuracy of the industrial robot FanucR-2000B 210F is 0.05 mm. This allows us to use it to calibrate the developed method.

3. Results
Ten experiments were conducted, in each of which the coordinates of the given points were determined. The mean values were chosen and the variance of the results obtained is given in the table below [7,8].

Table 3. Statistical indicators.

| Indicator | Point X₁ | Point X₂ | Point X₃ | Point Y₁ | Point Y₂ | Point Y₃ |
|-----------|----------|----------|----------|----------|----------|----------|
| Average   | 311,9367 | 156,8085 | 330,1928 | 346,4388 | 615,6469 | 835,5226 |
| Dispersion, $D[X]$ | 0,10485 | 0,1983 | 0,0841 | 0,2753 | 0,2176 | 0,3166 |
| CKO, $\sigma^2_X$ | 0,3238 | 0,4453 | 0,2899 | 0,5247 | 0,4665 | 0,5627 |
| $3 \cdot \sigma^2_Y$ | 0,9714 | 1,3359 | 0,8699 | 1,5741 | 1,3996 | 1,6882 |

Also of great interest is the removal of the spatial position of the gripper manipulator. A theoretical rationale is being worked out for 2 cameras and the use of stereo vision to estimate the spatial movement of a robotic gripper. To improve the accuracy of measurements, it is planned to retrofit the system with several light markers in mutually perpendicular planes.

As a result of the research, it can be concluded that the experimental data are in good agreement with the expected values. This method can be used to control various robotic systems that require positioning accuracy.

In the future, it is intended to generalize the method for different use cases. It is planned to increase the accuracy of the method by increasing the resolution of the camera, improving the camera.

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