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Simulation and Experimental Tests of Robot Using Feature-Based and Position-Based Visual Servoing Approaches

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1. Introduction

Discussion of visual control of robots has been introduced since many years ago. Related applications are extensive, encompassing manufacturing, teleoperation and missile tracking cameras as well as robotic ping-pong, juggling and etc. Early work fails to meet strict definition of visual servoing and now would be classed as look-then-move robot control (Corke, 1996). Gilbert describes an automatic rocket-tracking camera which keeps the target centered in the camera's image plane by means of pan/tilt controls (Gilbert et al., 1983). Weiss proposed the use of adaptive control for the non-linear time varying relationship between robot pose and image features in image-based servoing. Detailed simulations of image-based visual servoing are described for a variety of manipulator structures of 3-DOF (Webber & Hollis, 1988). Mana Saedan and Marcelo H. Ang worked on relative target-object (rigid body) pose estimation for vision-based control of industrial robots. They developed and implemented a closedform target pose estimation algorithm (Saedan & Marcelo, 2001). Skaar et al. use a 1-DOF robot to catch a ball. Lin et al. propose a two-stage algorithm for catching moving targets; coarse positioning to approach the target in near-minimum time and 'fine tuning' to match robot acceleration and velocity with the target.

Image based visual controlling of robots have been considered by many researchers. They used a closed loop to control robot joints. Feddema uses an explicit feature-space trajectory generator and closed-loop joint control to overcome problems due to low visual sampling rate. Experimental work demonstrates image-based visual servoing for 4-DOF (Kelly & Shirkey, 2001). Haushangi describes a similar approach using the task function method and show experimental results for robot positioning using a target with four circle features (Haushangi, 1990). Hashimoto et al. present simulations to compare position-based and image-based approaches (Hashimoto et al., 1991).

In simulating behavior and environment of robots many researches have been done. Korayem et al. designed and simulated vision based control and performance tests for a 3P robot by visual C++ software. They minimized error in positioning of end effector and also they analyzed the error using ISO9283 and ANSI-RIAR15.05-2 standards and suggested ways to improve error (Korayem et al., 2005, 2006). They used a camera which was installed on end effector of robot to find a target and with feature-based-visual servoing controlled end effector of robot to reach the target. But the vision-based control in this work is

implemented on 6R robot. The two cameras are mounted on the earth, i.e., the cameras observe the robot we can call the system "out-hand" (the term "stand-alone" is generally used in the literature). The closed-form target pose estimation is discussed and used in the position-based visual control. The advantage of this approach is that the servo control structure is independent from the target pose coordinates and to construct the pose of a target-object from 2 dimension image plane, two cameras are used. Image feature points in each of the two images are to be matched and 3-D information of the coordinates of the target-object and its feature points are computed by this system.

This chapter starts by introducing the 6R and 3P robots which are designed and constructed in IUST robotic research Lab. (Figs. 1, 2). Modeling and simulation process to solve direct and inverse kinematics of the robot are prescribed. After discussing simulation software of 6R and 3P robots, we simulated control and performance tests of robots and at last the results of tests according to ISO9283 and ANSI-RIAR15.05-2 standards and MATLAB are analyzed.



Fig. 1. 3P robot configuration.



Fig. 2. 6R robot configuration.

The robots were designed on the assumption that each joint has an independent DC motor actuator with gear reduction and measuring angular joint position sensor. In keeping with this, mechanical design of the robot was done using Mechanical Desktop and manufacturing process of the mechanical parts of the robot was developed. Kinematics and dynamics equations of the robots have been derived.

2. Kinematics Equations

Within kinematics one studies the position, velocity and acceleration, and all higher order derivatives of the position variables. The kinematics of manipulators involves the study of the geometric and time based properties of the motion, and in particular how the various links move with respect to one another and with time.

2.1 Direct kinematics of 3P robot

For an n-axis rigid-link manipulator, the *direct kinematics solution* gives the coordinate frame, or pose, of the last link. For 3P robot direct kinematics equations will be as follow:

$$T = A_1^0(d_1)A_2^1(d_2)A_3^2(d_3) \quad (1)$$

Where, d_1, d_2, d_3 are generalized coordinates. After expanding right side of the equation (1), we have:

$$T = \begin{bmatrix} 0 & 1 & 0 & w_1 \\ 0 & 0 & 1 & w_2 \\ 1 & 0 & 0 & w_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Where w_1, w_2, w_3 are prismatic joints displacement in x, y and z directions, respectively.

2.2 Inverse kinematics of 3P robot

Given a desired position and orientation for the end effector of robot, for finding values of the joint parameters which satisfy the direct equations (2), we need to solve inverse kinematics of robot. For 3P robot solving inverse kinematics equation, leads to:

$$\begin{cases} w_2 = d_3 \\ w_3 - d_1 = 0 \\ w_1 = d_2 \end{cases} \rightarrow \begin{cases} d_1 = w_3 \\ d_2 = w_1 \\ d_3 = w_2 \end{cases} \quad (3)$$

2.3 Direct kinematics of 6R robot

According to the Denavit-Hartenberg notation for the 6R robot, Table of the D-H parameters will be as follow:

| AXIS | θ | d | a | α |
|------|------------|-------|-------|----------|
| 1 | θ_1 | d_1 | 0 | $-\pi/2$ |
| 2 | θ_2 | 0 | a_2 | 0 |
| 3 | θ_3 | 0 | a_3 | 0 |
| 4 | θ_4 | 0 | a_4 | $\pi/2$ |
| 5 | θ_5 | 0 | 0 | $-\pi/2$ |
| 6 | θ_6 | d_6 | 0 | 0 |

Table 1. Kinematics parameters for the 6R robot

According to Table 1 by multiplying the link transform matrices for the robot, the total transformation matrix will be:

$${}^0_6T = {}^0_1T {}^1_2T {}^2_3T \dots {}^5_6T \quad (3)$$

0_6T determines position and orientation of end effector with respect to base coordinate. If positions of joints are determined by position sensors, the pose of end effector will be determined according to 0_6T . For 6R robot this matrix will be as follow:

$$T_0^6 = \begin{bmatrix} n_x & o_x & a_x & P_x \\ n_y & o_y & a_y & P_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Where:

$$n_x = C_1(C_5C_6C_{234} - S_6S_{234}) - S_1S_5C_6 \quad n_y = S_1(C_5C_6C_{234} - S_6S_{234}) + C_1S_5C_6 \quad n_z = -C_5C_6S_{234} - S_6C_{234}$$

$$\begin{aligned}
P_x &= -C_1(d_6S_5C_{234} - a_4C_{234} - a_3C_{23} - a_2C_2) - d_6S_1C_5 & o_y &= -S_6(C_5S_1C_{234} + C_1S_5) - C_6S_1S_{234} & o_z &= S_{234}C_5S_6 - C_6C_{234} \\
P_z &= d_6S_5S_{234} - a_4S_{234} - a_3S_{23} - a_2S_2 + d_1 & o_x &= -C_1(C_5S_6C_{234} + C_6S_{234}) + S_1S_5S_6 & a_x &= -C_1S_5C_{234} - S_1C_5 \\
P_y &= -S_1(d_6S_5C_{234} - a_4C_{234} - a_3C_{23} - a_2C_2) + d_6C_1C_5 & a_y &= -S_1S_5C_{234} + C_1C_5 & a_z &= S_{234}S_5
\end{aligned}$$

Using the notational shorthand as follow:

$$\cos \theta_i = C_i, \quad \sin \theta_i = S_i, \quad \cos(\theta_i + \theta_j) = C_{ij}, \quad \sin(\theta_i + \theta_j) = S_{ij}$$

2.4 Inverse kinematics of 6R robot

For a given desired position and orientation of the end effector in order to find values for the joint angles which satisfy the direct equations, we need to solve inverse kinematics of robot. Inverse kinematics equations for the 6R robot will be as follow:

$$\theta_1 = \tan^{-1} \left(\frac{P_y - d_6 a_y}{P_x - d_6 a_x} \right) \quad \text{and} \quad \theta_1 = \theta_1 + \pi \quad (5)$$

$$\theta_5 = \tan^{-1} \left(\frac{\pm d_6 [1 - (a_y C_1 - a_x S_1)^2]^{1/2}}{P_y C_1 - P_x S_1} \right) \quad (6)$$

$$\theta_6 = \tan^{-1} \left(\frac{o_x S_1 - o_y C_1}{n_y C_1 - n_x S_1} \right) \quad \text{for } \theta_5 > 0 \quad \text{and} \quad \theta_6 = \theta_6 + \pi \quad \text{for } \theta_5 < 0 \quad (7)$$

$$\theta_{234} = \tan^{-1} \left(\frac{-a_z}{a_x C_1 + a_y S_1} \right), \quad \text{if } \theta_5 > 0, \text{ else } \theta_{234} = \theta_{234} + \pi \quad (8)$$

$$\theta_2 = -\tan^{-1} \left(\frac{\pm [1 - (w/q)^2]^{1/2}}{w/q} \right) + \tan^{-1} \left(\frac{u}{t} \right) \quad (9)$$

$$\theta_3 = \tan^{-1} \left(\frac{u - a_2 S_2}{t - a_2 C_2} \right) - \theta_2, \quad \theta_4 = \theta_{234} - \theta_2 - \theta_3 \quad (10,11)$$

Where:

$$\begin{aligned}
t &= P_x C_1 + P_y S_1 + d_6 S_5 C_{234} - a_4 C_{234}, \quad u = -p_z + d_1 - a_4 S_{234} + d_6 S_5 S_{234} \\
w &= \frac{t^2 + u^2 + a_2^2 - a_3^2}{2a_2}, \quad q = \sqrt{t^2 + u^2}
\end{aligned}$$

Above equations are used to simulate robot motion.

3. Dynamic Equations

Manipulator dynamics is concerned with the equations of motion, the way in which the manipulator moves in response to torques applied by the actuators, or external forces. The equations of motion for an n -axis manipulator are given by:

$$\vec{Q} = M(\vec{q})\ddot{\vec{q}} + C(\vec{q}, \dot{\vec{q}})\dot{\vec{q}} + F(\dot{\vec{q}}) + G(\vec{q}) \quad (12)$$

Where \vec{q} is the generalized joint coordinates vector; M is the symmetric joint-space inertia matrix; C describes Coriolis and centripetal effects.

F describes viscous and Coulomb friction and is not generally considered part of the rigid-body dynamics; G is the gravity loading and Q is the vector of generalized forces associated with the generalized coordinates q .

3.1 Dynamic equations of 3P robot

$$\begin{aligned} F_1 &= (m_1 + m_2 + m_3 + m_p)\ddot{d}_1 - g(m_1 + m_2 + m_3 + m_p); \\ F_2 &= (m_2 + m_3 + m_p)\ddot{d}_2 \\ F_3 &= (m_3 + m_p)\ddot{d} \end{aligned} \quad (13)$$

Where m_1, m_2, m_3 and m_p are masses, F_1, F_2, F_3 are input torques to motors No. 1, No. 2 and No. 3, respectively.

3.2 Dynamic equations of 6R robot

Dynamic equations of the 6R robot, based on equation 12, are derived by means of Lagrange-Euler method and also Newton-Euler method, using Mathematica software. Dynamic equations which derived by these two individual methods, are compared with each other. The simplified dynamics equation for 5th joint which is simplified by assuming the angular velocity of all the six joints are approximately zero is as follows:

$$\begin{aligned} \tau_5 &= -\frac{1}{2}g(C_{234}C_5S_1 + C_1S_5)d_6m_6 + \frac{1}{4}\left[4C_5(S_{234}S_6C_6(I_{xx_6} - I_{yy_6})\dot{\theta}_1 \right. \\ &- d_6m_6(S_{34}a_2\ddot{\theta}_2 + S_4a_3(\ddot{\theta}_2 + \ddot{\theta}_3))) + 2S_5((-a_1 - C_2a_2 - C_{23}a_3 - C_{234}a_4) \\ &d_6m_6\ddot{\theta}_1 - 2S_6C_6(I_{xx_6} - I_{yy_6})(\ddot{\theta}_2 + \ddot{\theta}_3 + \ddot{\theta}_4) + (4(S_6^2I_{xx_6} + I_{yy_5} + C_6^2I_{yy_6}) \\ &\left. + d_6^2m_6)(C_{234}\ddot{\theta}_1 + \ddot{\theta}_5)\right] \end{aligned} \quad (14)$$

4. Simulator software

For increasing the efficiency of designed robots packages for simulation of control and movement of robots are developed. In these packages by using a designed interface board, movement signals to control the robots are sent to robot.

4.1 simulation package for 6R robot

To improve the applications of 6R robot a software operating in windows system was written in Visual Basic programming language. In this program kinematics equations for robot are solved and simulated graphically. This simulator software has different parts such as "Direct Kinematics, Inverse Kinematics, Direct Dynamics, Inverse Dynamics, Path Planning Control and Experiments". Main menu of program is shown in Fig. 3.



Fig. 3. Main menu of 6R robot program.

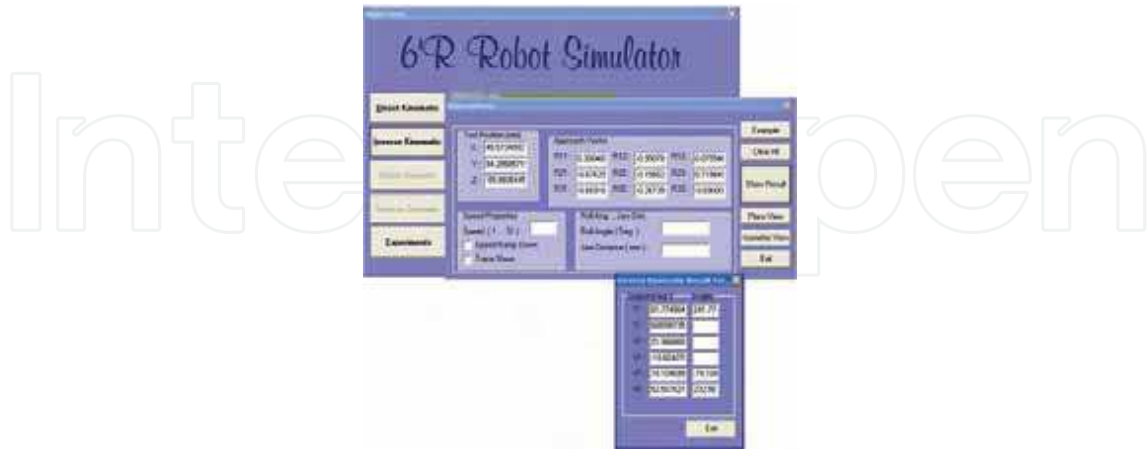


Fig. 4. Inverse kinematics and graphical simulation menu of 6R robot.

In direct kinematics Section, user by entering joint parameters can obtain the position and orientation of end effector. In inverse kinematics Section for a given position and approach vector joint parameters are computed (Fig. 4). In point to point Section, user can define pose of tool for more than one point. Also a smooth curve for path of the end effector, path trajectory and torque curves can be obtained. Joints torques is computed using sliding mode control algorithm.

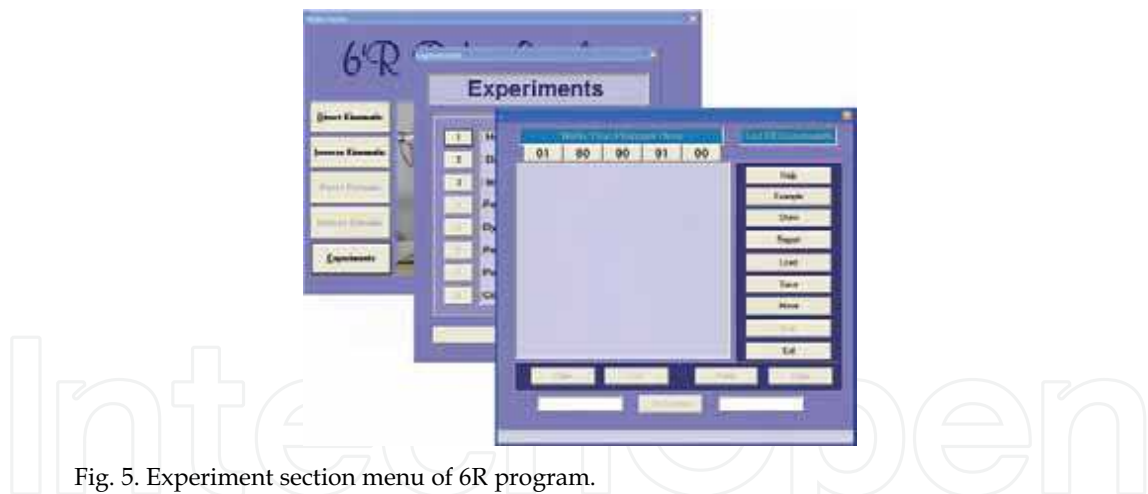


Fig. 5. Experiment section menu of 6R program.

In experiments part after selecting one of designed experiments, user can define codes for robot motion according to experiments instruction and simulation results and data can be reported (Fig. 5).

4.2 simulation package for 3P and 6R robots

To simulate control and test of 6R and 3P robots, we have used object oriented software Visual C++6. This programming language is used to accomplish this plan because of its

rapidity and easily changed for real situation. In this software, the picture is taken in bitmap format through two fixed cameras which are mounted on the earth or by a camera which is installed over the end effector in the capture frame module and it is returned in form of array of pixels. Image capturing is switched between two cameras. After image processing, objects in pictures are saved separately, features are extracted and target-object and end effector will be recognized among them according to their features. Then position coordinates of target-object and end effector are estimated. After each motion of joints new picture is taken from end effector and this procedure is repeated until end effector reach to target-object.

With images from these two fixed cameras or camera on the end effector, positions of objects are estimated in image plane coordinate, usually, to transform from image plan coordinates to the reference coordinates system, mapping and calibrating will be used. In this program, in order to do this mapping which is a non-linear mapping, we have used a neural network to transform these coordinates to global reference coordinate. Mapping system needs extra work and is complicated compared to neural network. Neural networks are used as nonlinear estimating functions. To compute processing matrix, we have used a set of points to train the neural system. This collection of points are achieved by moving end effector of robot through different points which their coordinates in global reference system are known and their coordinates in image plane are computed by vision module in simulator software. The position of the end effector is recognized at any time by two cameras which are fixed with a certain distance from each other. The camera No.1 determines the target coordinates in a 2-D image plan. The depth of the picture also is computed by the second camera.

The used neural network, is a backpropagation perception kind network with 5 layers which in the first layer a 4 node entrance including picture plan coordination, layers 2, 3 and 4 take 20 node and finally output layer, 3 node including coordinates x , y and z in the earth-reference system.

4.2.1 Labeling process

The main aim of this process is allocated an exclusive index to any district in binary image through which all pixels having any quality except zero will be related with each other. Iterative labeling algorithm will analyze entrance on the image and each time a free and no related pixel is found, a new label is allocated to it. If any related, but having different labels district is seen, a series of iterative label will be published and both districts get new label, so that the least number of the labels are used. Iterative algorithm is very simple but too much slow, significantly when there are some U form object in the picture, labeling algorithm of equivalence table uses a table which registers the equivalences between the labels. Whenever the two related districts are seen with different labels, new entrance will be opened in equivalences schedule. The last process has been done by reallocation of the labels using research techniques in the graph. There will be an excessive difference, computing above mentioned approaches expenses costs. For instance, a picture in 700×356 sizes, which is labeled by iterative algorithm, takes about 50 seconds, while the necessary period for the algorithm using equivalences table is about 12 seconds.

Two processes are needed in equivalences table algorithm. The first process is the primary labeling and the second one, is to merge neighborhood labels by equivalences table. Because of this research being on-line, the 12-second period seems to be too much for the labeling task. So, another algorithm was created which could check for every non-free pixel and calculate to find if there. If the response is positive, the act of merging will be done in the

same place and after merging, the task of labeling will be continued. The period spent for this algorithm will be decreased to two seconds (Korayem et al., 2005).

5. Simulation of controlling the robots

We have used feature based and position based visual servoing systems to control 3P and 6R robots. In this part of simulator software, position and orientation of end effector is controlled by using two fixed cameras for 6R robot and by one camera mounted on end effector of 3P robot. By estimating pose of end effector it will be moved to reach the target-object. In each motion of end effector the camera(s) will take pictures from target-object and end effector and its environment, then they will be recognized according to feature based visual servoing for 3P robot or position based visual servoing for 6R robot.

5.1 3P robot control

To simulate control of 3P robot, two cameras have been used. The user can observe the environment by switching between two cameras at any moment. The task of the processor camera which has been installed on the end effector is getting pictures from workspace and sending them to the vision system for information process. The second camera is the observer camera. The aim of installation of such camera is observing the whole space where the robot is moving and working and also its reaction will be observed by user. This camera is moveable and the user can change its position and orientation arbitrarily.

Picture frames taken by cameras are kept in a buffer in pixel format. Series of frames are also kept in buffer series. After segmentation, objects in the collection of the frames are labeled and separated. After threshold operations, segmentation, and labeling, the present objects in the *buf1* picture will be extracted and each single frame is conserved in different levels of the *obj* frames collection with its number. The target-object should be recognized among them after separation of the objects. Target will be recognized according to its features and properties. The approach used to control the end effector reaching to the target-object is the *feature-based visual control servoing*. Here, only one camera has been used for controlling the process.

In this controller process the displacements between target-object and the end effector is computed to correct delta X and delta Y, distance between end effector and target-object in x and y directions. Then necessary commands will be given to X and Y axis of the robot to move the end effector. After the above-mentioned displacements, another image will be taken from the workspace and the operations will be repeated. This process will be repeated until the robot's X and Y axis' error are getting the least amount possible. This algorithm tries to observe the target-object in the center of the image plane each moment and the distance errors between the end effector and target-object is computed according to the distance of center of object and the center of the image plane of camera mounted on the end effector. Then, delta Z is computed and rectified. This duty will be done just like the former case, but this axis error, is corrected based on the size of the object, observed in the image plane, the real size of object is known and it will be compared to the size observed in the image plane and the end effector will move till this difference reach to the least possible amount.

There are different kinds of objects in the robot workspace. Robot identifies the desired object which is a spherical shape by its feature in visual system and leads the end

effector to it. Visual system carries out this process in 34 steps. Figs 6, 7 show the robot in the first step and Figures 7 shows the robot in the last step after reaching to the target-object (34th step).

In this part of simulator software standard performance tests of robot also can be done without any limitation and the results can be observed quite naturally as well as controlling the end effector to find and reach the target-object automatically through the vision system.



Fig. 6. Robot picture after the first step

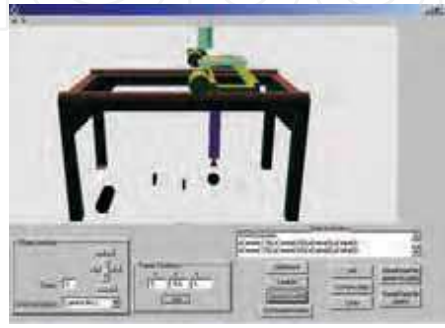


Fig. 7. Robot picture after reaching to the target

The robot can read and perform its motion in two approaches; the first process is point to point. In this approach, the rate of moving end effector in the space can be determined in the file that has been loaded before by the user in such a way of line after line and will be read and done through the program. The second approach is a continuous path and the user can determine paths such as circle (parameters: center and radius), rectangle (parameters: the length of the lines and coordination of corner), line (parameters: coordination of start and end points) for the robot motion.

5.2 6R robot control

To simulate control of 6R robot, the picture is taken in bitmap format by two fixed cameras which are mounted on the earth i.e., the cameras observe the robot we can call the system "out-hand" (the term "stand-alone" is generally used in the literature) then it is returned in form of array of pixels in a buffer. Image capturing is switched through two cameras it means that both cameras take photograph from robot and its surrounding and their images will be processed. After image processing objects in pictures are saved separately and their features are extracted and target-object and the end effector will be recognized among them according to their features and properties. Then position coordinates of target-object and end effector are estimated. After each motion of joints new picture is taken from end effector and this procedure is repeated until end effector reach to target-object.

With images from these two fixed cameras positions of objects are estimated in image plane coordinate, to transform these coordinates to global reference coordinate, we have used a neural network as described before. Computing 3D position of the end effector and target-object is possible by using images from these two fixed cameras. This approach used to control the end effector reaching to the target-object is the *position-based visual servoing control*. The advantage of this approach is that the servo control structure is independent from the target pose coordinates and to construct the pose of a target-object from two dimension image plane, two cameras are used. Image feature points in each of the two

images are to be matched and 3-D information of the coordinates of the target-object and its feature points are computed by this system.

In this algorithm, pictures taken by two cameras are saved in arrays of pixels and after threshold operations, segmentation, and labeling, the objects in the pictures will be extracted and each single frame is conserved separately with its number. The target-object and end effector should be recognized among them after separation of the objects according to their features and properties. Distance between end effector and target-object will be estimated, by using inverse kinematics equations of 6R robot, each joint angle will be computed then by revolution of joints end effector will approach to target. In each step cameras take image and the process will repeat until end effector reach to target and its distance to target-object gets the least possible amount. Control procedure of robot to reach to target-object is briefly shown in Figs. 8-11.



Fig. 8. 6R robot in home position (view camera1)



Fig. 9. Robot picture after some steps to reach to target.



Fig. 10. Robot picture after reaching the end effector to target.



Fig. 11. The robot picture after reaching the end effector to target (view camera2).

6. Simulation of performance tests of robots

The designed robots should accomplish the given commands accurately and smoothly. This is possible in the case that the motion of the end effector of the robot is accurate enough relative to the target-object that is the point that the end effector of the manipulator has reached to. The accuracy of actual robot is under the effect of the following factors:

- 1) The accuracy of manufacturing mechanical parts of the robot.
- 2) The accuracy of assembling the constituting part of robot.
- 3) Accuracy during the robot operation that is influenced by external forces.
- 4) Electronics system accuracy and motors motion
- 5) The clearance existing in the system
- 6) Wear behaviours, that is change in accuracy of the robot in long duration
- 7) Change in accuracy of system after assembling the disassembled parts due to repair

So in simulator program these errors are figuratively inserted. Despite the recent international efforts by many of the standard committees, research and industrial labs, many of the robots users still sustain a loss, as a result of the lack of the standard, technical approaches and necessary determinations of the robot examinations. This matter is caused by complexity of the most robot designations and their vast limitations. In this research we try to do some of these approaches by using camera and visual system according to the standards such as ISO-9283, and ANSI-RIA.

The aim of these standards is providing technical information to help users to select the most convenient robot for their purposes. These standards define important principles based on the path, and then different appearances will be seen to evaluate them. These principles are: approximate accuracy of the path, absolute accuracy of the path repetition ability of the path rapidness specifications, and corner variable. Evaluation of the mentioned principles is one of the most convenient ways for evaluation of the whole activity based on industrial robots path. Also, the measurement of these principles brings the opportunity of comparing similar robots operations. To make tests more applicable, statistic analyzes according to ANSI-RIA or ISO9283 standards are performed.

6.1 Performance test of 3P robot

In second version of software the performance tests of the robot according to the international standards known as ISO 9283 and ANSI/RIA R15.05-2 have been accomplished. Two cameras with a certain distance from each other are looking at the end effector. One of these two cameras is fixed and zooms at the end effector. Position of end effector is determined in image plane and then is transferred to global coordinate by using neural network. For 3P robot performance tests which are implemented by camera and visual system are accomplished and performance parameters of robot are estimated. The end effector of 3P robot is moved on a special direction in different paths like circular and rectangular paths. The position of the end effector is recognized at any moment by two cameras which are fixed with a certain distance from each other. In this approach contrary to the former one, the camera is not on the end effector. The camera No.1 determines the target coordination in a 2-D image plan. The depth of the picture also is computed with the help of the second camera. Results of these tests are shown in Figs. 12, 13. (Korayem et al., 2005).

6.2 Performance test of 6R robot

In this research, by two fixed cameras on the ground we have simulated performance tests of 6R robot. Monitoring is possible with each of cameras. After image processing and recognition of the end effector and estimating its coordinate in image plane, by neural network this coordinate are transformed to global reference coordinate.

In this version of software, performance tests of robot including direct kinematics, inverse kinematics and motion of end effector in continues paths like circle, rectangle and line is possible. For point to point moving of end effector, each joint angle is determined and robot will move with joints rotation. In inverse kinematics test, desired position and orientation of end effector is determined in transformation matrix T . amount of joint angles which satisfy inverse equations will be found and wrist will be in desired pose. Two observer cameras take pictures and pose of end effector will be estimated to determine positioning error of robot.

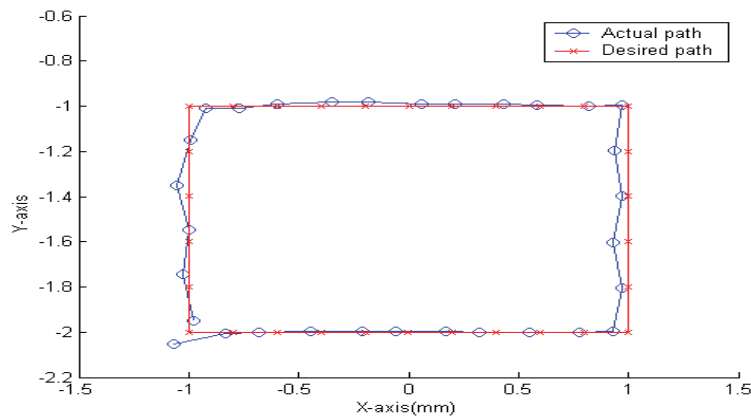


Fig. 12. Error investigation in variant rectangular path (by two cameras).

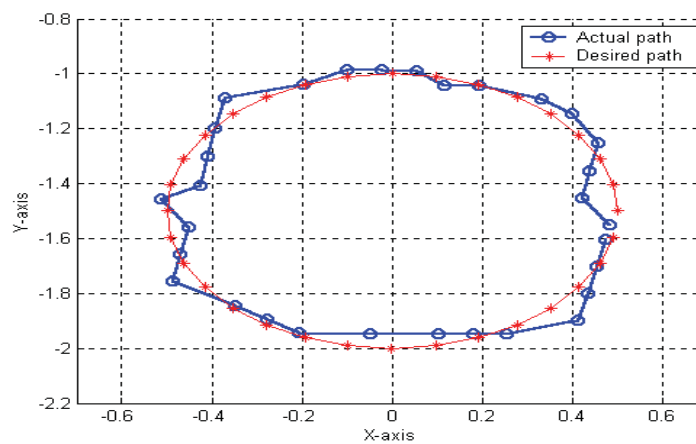


Fig. 13. Error investigation in circular path.

Then using ISO9283, ANSI-RIA standards, these errors will be analyzed and performance characters and accuracy of the robot will be determined. Results of these standard tests are used to compare different robots and their performance. In this research we try to do some of these tests by using camera and visual system according to the standards such as ISO-9283, and ANSI-RIA that belong to the robot specifically.

6.2.1 Performance test of 6R robot according to ISO9283 standard

The test operating approaches to specify robot parameters in this standard are divided into eight categories. In this research, two approaches among them which are done with camera and visual system are implemented to measure the path related parameters of 6R robot.

6.2.1.1 Direct kinematics test of 6R robot (point to point motion)

In this part of test position accuracy and repeatability of robot is determined. With rotation of joints end effector will move to desired pose. By taking pictures with two fixed cameras and trained neural network, we will have position of end effector in global reference frame. To determine pose error these positions and ideal amounts will be compared. Positioning error in directions x , y , z for 10 series of direct kinematics tests is shown in Fig. 14.

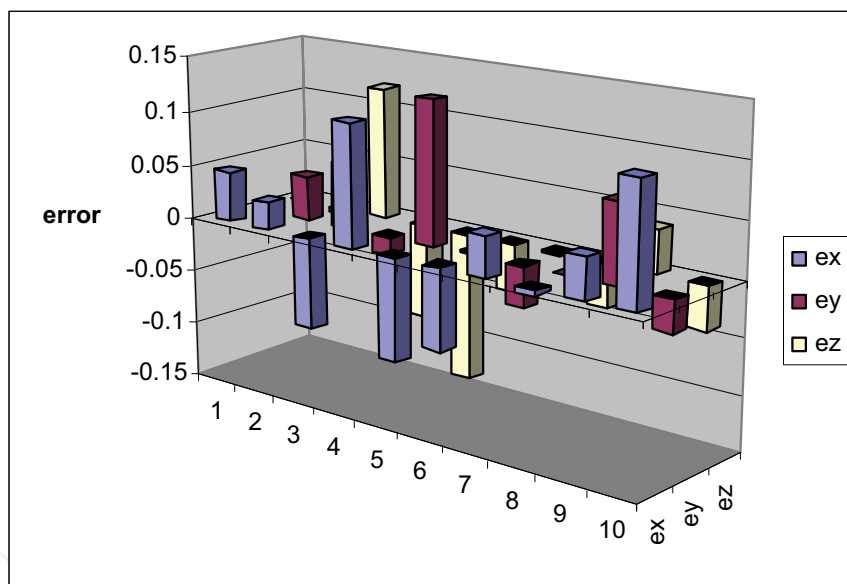


Fig. 14. The error schematics in x, y, z directions for direct kinematics tests.

6.2.1.2 Inverse kinematics test

In this stage, desired pose of end effector is given to robot to go there. By computing joint angles from inverse kinematics equations and rotation of joints, end effector will go there. By taking pictures with two fixed cameras and trained neural network, we will have position coordinates of end effector in global reference frame. By comparing the ideal amounts of pose and real one, the positioning error will be determined. Positioning error in directions x , y , z for 10 series of inverse kinematics tests is shown in Fig.15.

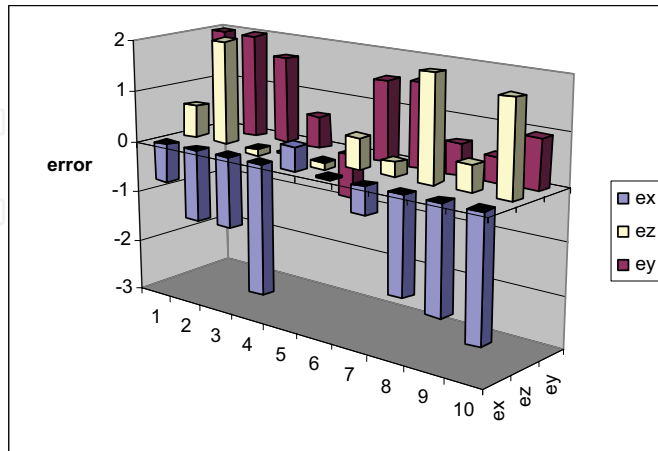


Fig. 15. The error schematics in x , y , z directions for inverse kinematics tests.

6.2.1.3 Continues path test

To determine accuracy of robot in traversing continues paths wrist of robot is guided along different paths. In simulator software, 3 standard paths are tested.

a) Direct line

To move end effector along a direct line its start and end points must be determined. Approach vector direction is normal to direction of line path i.e. wrist is always normal to its path. With pose of end effector and inverse kinematics equations of robot joint angles will be computed. Joints rotate and end effector will be positioned along its path. Coordinates of end effector in global reference frame is determined by taking pictures with two fixed cameras and trained neural network.

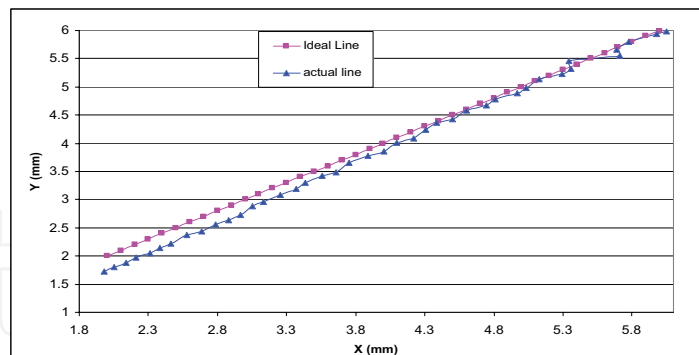


Fig. 16. The error investigated in line path.

The positioning error is determined by comparing the ideal pose and real one. Error of robot in traversing direct line path is shown in Fig.16.

b) Circular path

We investigate the accuracy, repeatability and error of robot on the circular continuous path traversing. Circle is in horizontal plane i.e. height of end effector is constant from earth level. Orientation of wrist is so that end effector is always in horizontal plane and normal to

circular path and wrist slides along perimeter of circle. In this way sliding, approach and normal vectors are determined and inverse kinematics equations can be solved. During motion of wrist on the path, 32 images have been taken from end effector using two cameras. In this way, end effector coordinates in image plan will be collected. Using neural network, image plan coordinates of points will be transformed to the reference frame. The desired path and actual path traversed by robot is shown in Fig. 17.

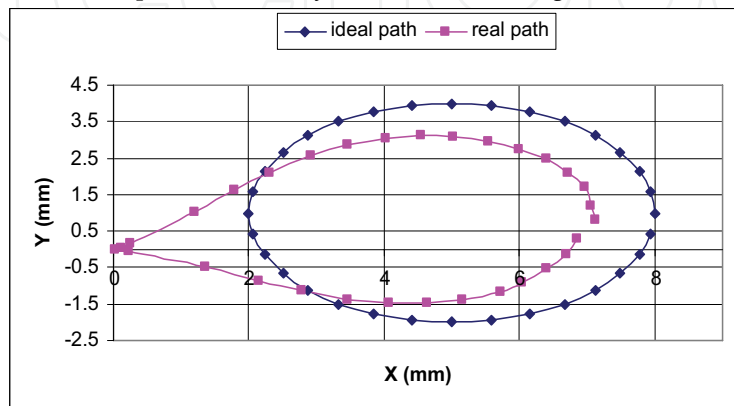


Fig. 17. The error investigated in circular path.

c) *Rectangular path*

Error of moving the wrist of robot along rectangular path is also considered. In order to do this, we define vertex coordinate, length and width of rectangle for the robot. Orientation of end effector is tangent to path. In this way transformation matrix of end effector is determined, then inverse kinematics equations are solved and end effector moves in this path, we take image from the end effector by the two cameras fixed on the earth. The desired path and actual path for rectangle r -3, -4, 10, 8 have been drawn in Fig. 18.

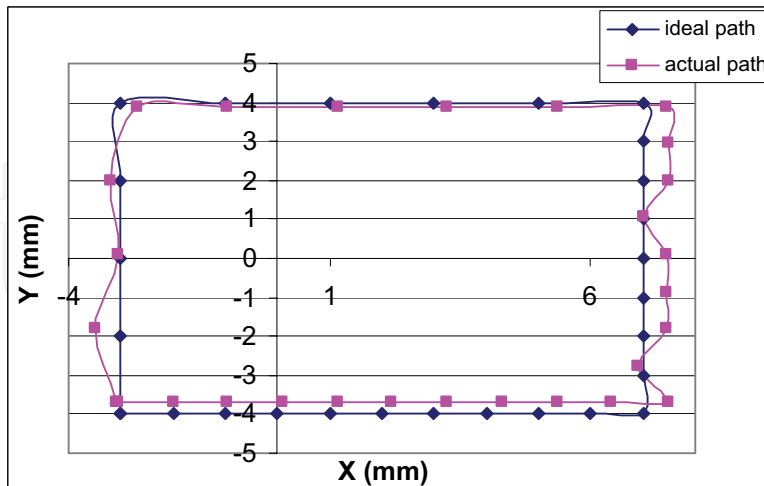


Fig. 18. The error investigated in rectangular path.

6.2.2 Robot performance test based on the American standard ANSI-RIA R15.05-2

The aim of this standard is providing technical information to help users to select the most convenient case for the robot. This standard defines important principles based on the path, and then different methods will be introduced to evaluate them. These principles are: approximate accuracy of the path, absolute accuracy of the path repetition ability of the path rapidness specifications, and corner variable. Evaluation of the mentioned principles is one of the most convenient ways for evaluation of the whole activity based on industrial robots path. Also, the measurement of these principles brings the opportunity of contrasting similar robots operations. To make tests more applicable, statistic analyzes according to ANSI-RIA standard are performed on the achieved out puts in the former sections (Korayem et al., 2005).

6.2.2.1 Circular and rectangular path

In this standard for rectangular paths at least 20 evaluating points and for circular path least 12 evaluating points must be used, that we have used 32 evaluating points for tests.

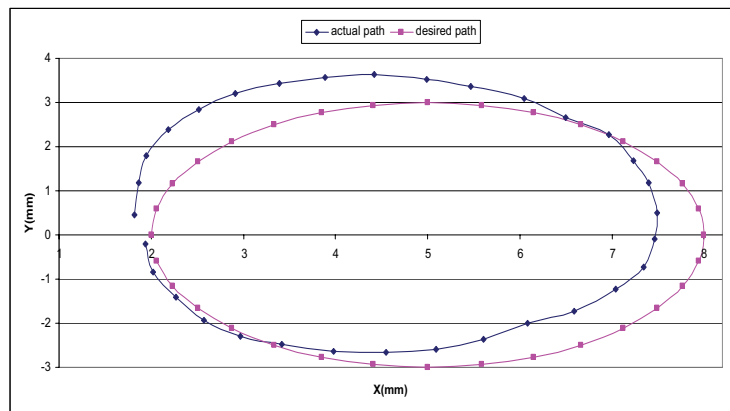


Fig. 19. The error investigated in circular path according to ANSI standard.

7. Error analysis of the 6R robot

Now we analyze results of previous tests according to different standards and we determine performance parameters and accuracy of 6R robot.

7.1 Error analysis according to ISO9283

In this standard some performance parameters of robot to position and path traversing such as pose accuracy and repeatability are determined. For direct and inverse kinematics test of 6R robot results are as follow. Bary center and mid point for test one is:

$$\bar{x} = -0.04, \bar{y} = 7.4, \bar{z} = 2.01$$

Pose accuracy for the robot which means error in positioning of end effector is computed as follow:

$$AP_p = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2}$$

$$AP_x = (\bar{x} - x_c), \quad AP_y = (\bar{y} - y_c), \quad AP_z = (\bar{z} - z_c) \quad (15)$$

Orientation accuracy is:

$$AP_a = (\bar{a} - a_c), \quad AP_b = (\bar{b} - b_c), \quad AP_c = (\bar{c} - c_c) \quad (16)$$

Pose repeatability is accuracy and error between attained pose and command pose after n repetition of test. Repetition n in these tests is 30. For a given pose repeatability is defined in (ISO9283, 1998).

Path accuracy, maximum drift of position and orientation AT_p is maximum deviation between command positioning of path and Bray center G_i in n test cycles. Path accuracy AT is computed as follow:

$$AT_p = \max \sqrt{(x_i - x_{ci})^2 + (y_i - y_{ci})^2 + (z_i - z_{ci})^2} \quad i = 1, 2, \dots, m \quad (17)$$

Where x_{ij}, y_{ji}, z_{ij} are coordinate of intersection point between jth path and ith normal plane, and x_{ci}, y_{ci}, z_{ci} are coordinate of ith point of command path. Pose accuracy and path accuracy for the 6R robot in our tests are listed in Table 2.

| | AP | RP | AT | RT |
|-----------|------|------|------|------|
| dir. kin | 0.42 | 0.4 | - | - |
| inv. Kin | 0.98 | 1.05 | - | - |
| line | - | - | 0.65 | 0.85 |
| circle | - | - | 1.82 | 2.04 |
| rectangle | - | - | 0.78 | 0.92 |

Table 2. Pose accuracy & repeatability according to ISO9283 standard

7.2 Error analysis according to standard ANSI-RIA

Results of simulated tests in previous sections are analyzed with standard ANSI-RIA to compare with results of ISO9283.

(v_{aj}, u_{aj}) correspond to the coordinates of the Bary center path on evaluating plane. m is number of points in path and n is number of repetition. Their centers are $\bar{u}_{aj}, \bar{v}_{aj}$.

The mean reference path is used in the evaluation of the path repeatability FOM. This process involves the calculation of the deviation of D_{ij} between an evaluated point and its corresponding Bary center point (Korayem et al., 2005).

Cornering round off CR is defined as the minimum distance between the corner point and any point on the attained path. For each of the three corner points, the value for CR is calculated as follows:

$$CR = \min_{k=1}^k \sqrt{(X_e - X_{ak})^2 + (Y_e - Y_{ak})^2 + (Z_e - Z_{ak})^2} \quad (18)$$

Where X_e, Y_e, Z_e are the position coordinates for each of the reference corner points and X_{ak}, Y_{ak}, Z_{ak} are the coordinate of points along the attained path.

Cornering overshoot CO is defined as the largest deviation outside of the reference path after the robot has passed the corner. Its value is the maximum distance between the reference path and the attained path:

$$CO = \max_{k=1}^k \sqrt{(X_e - X_{ak})^2 + (Y_e - Y_{ak})^2 + (Z_e - Z_{ak})^2} \quad (19)$$

Where X_{ak} , Y_{ak} and Z_{ak} are the position coordinates for discrete data points on the attained path. X_{rk} , Y_{rk} and Z_{rk} are the coordinates of the sample data points along reference path traversed by the robot.

To compute performance criteria of robot, end effector is guided along rectangular path based on standard platform (Korayem et al., 2005). The number of points for evaluation would be $m = 34$ and this will be repeated 10 times ($n = 10$). Two cameras, observing the end effector with at fixed distance in specified periods, take picture from end effector and its environment and its coordinates are achieved from image plan with position based visual system. To transform coordinates of wrist of robot to the reference frame as mentioned before, in this work we have used neural networks. Using neural networks we map coordinates from image plan into reference system, in order to have real distances.

Maximum repeatability is $PR = 0.375$ and average of repetition is $\overline{PR} = 0.264$ also CR corner deviation error and CO cornering overshoot for the tests simulated are listed in Table 3.

| Reference | CR | CO |
|-----------|-------|-------|
| P1 | 0.125 | 3.251 |
| P2 | 0.098 | 3.320 |
| P3 | 0.178 | 3.78 |

Table 3. Repeatability & cornering overshoot according to ANSI standard

Where corner coordinates are:

$$P_1 = (2,3), P_2 = (1,1), P_3 = (-2,-3)$$

7.3 Error analysis with software MATLAB

Considering and analysis of direct and inverse kinematics tests data also has been done by software MATLAB. Error histograms in x and y direction for direct kinematics test is shown in Figs. 20, 21.

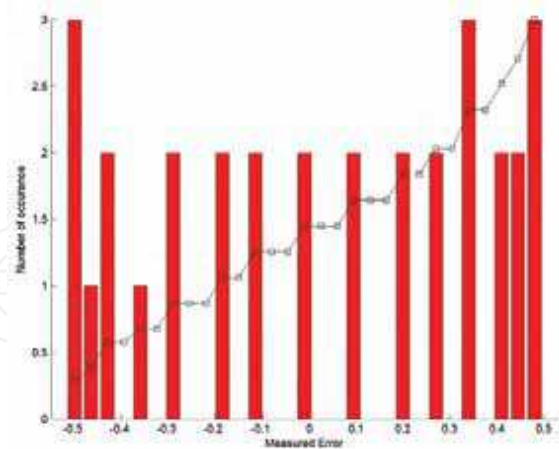


Fig. 20. The error histogram in x direction.

Mean value of error in x direction is 0.0376 with standard deviation equal to 0.353 and error skewness of -0.184.

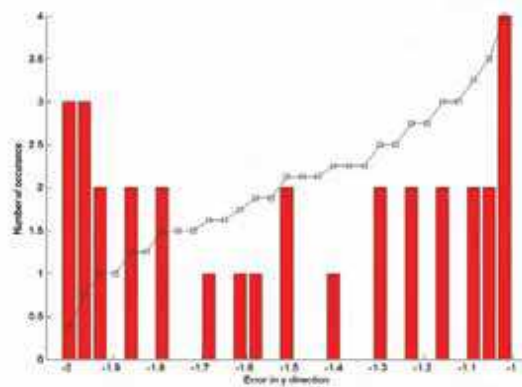


Fig. 21. The error histogram in y direction.

Mean value of error in y direction is -1.49 with standard deviation equal to 0.337 and error skewness of -0.0157.

For inverse kinematics tests, also error histograms in x and y directions are shown in Figs. 22, 23.

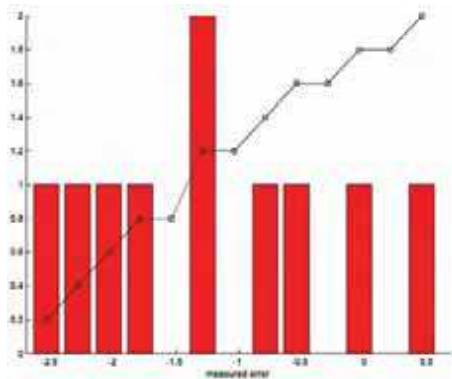


Fig. 22. The error histogram in x direction for inverse kinematics tests.

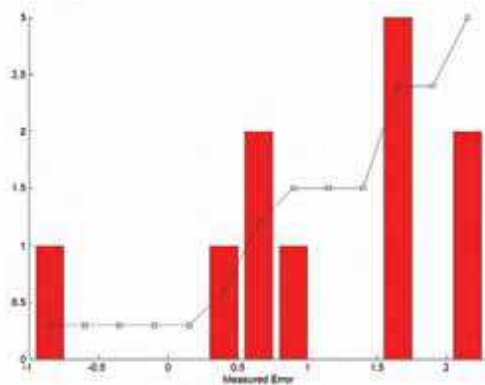


Fig. 23. The error histogram in y direction for inverse kinematics tests.

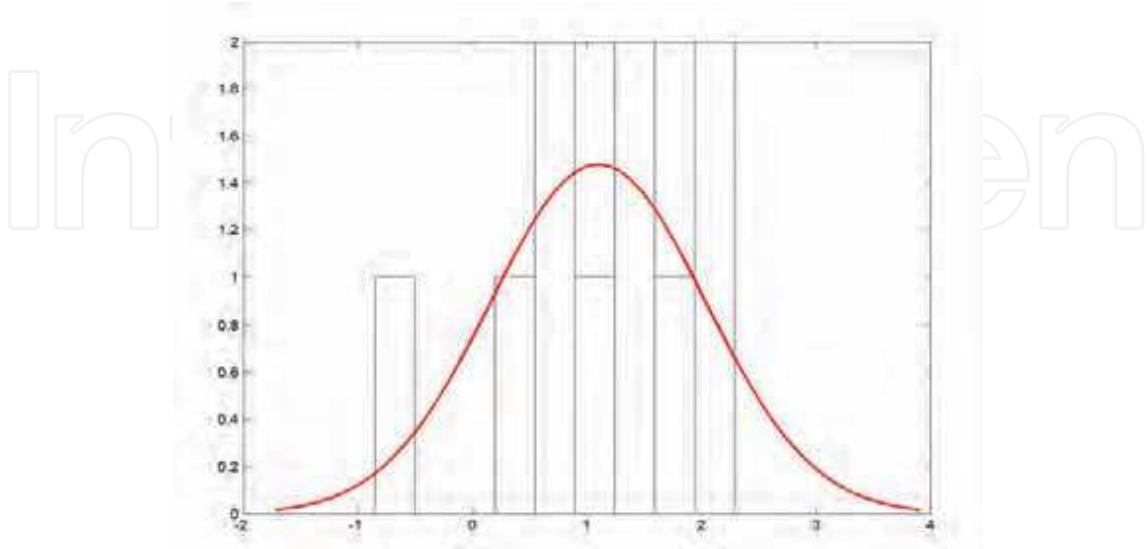


Fig. 24. Histogram with superimposed normal distribution for error in x direction.

To show normality of tests error we superimposed histogram of errors with corresponding normal plot which results in Figs. 24, 25.

To see whether or not the data are normally distributed we plot the graphs in Figs. 26, 27. It is seen that a fairly large portion of our data are close to the straight line, leading one to conclude that normal distribution is a reasonable approximation to these data.

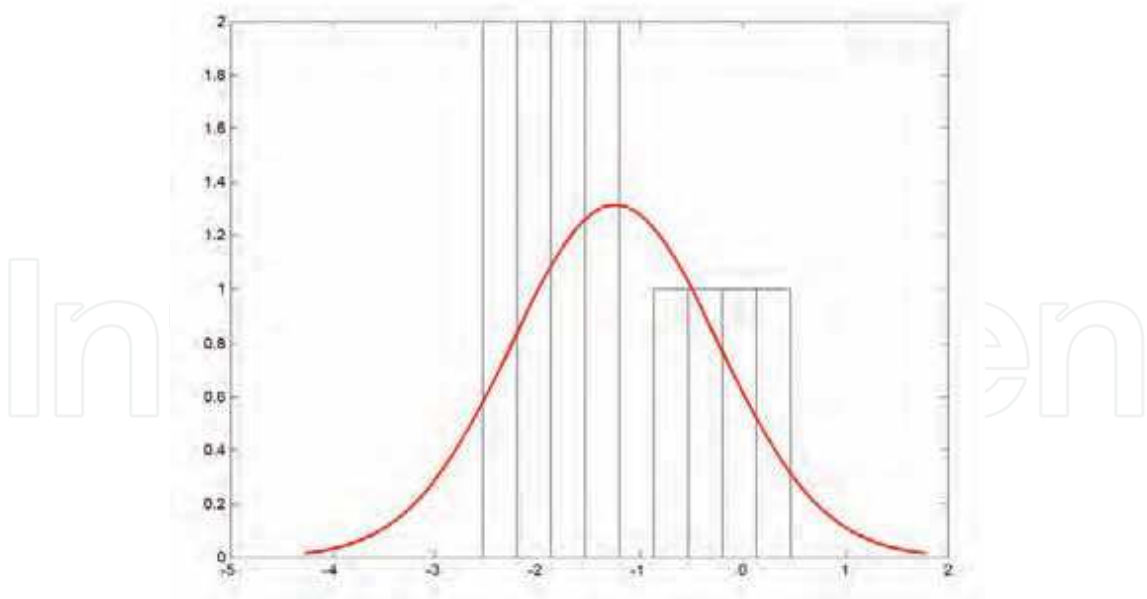


Fig. 25. Histogram with superimposed normal distribution for error in y direction.

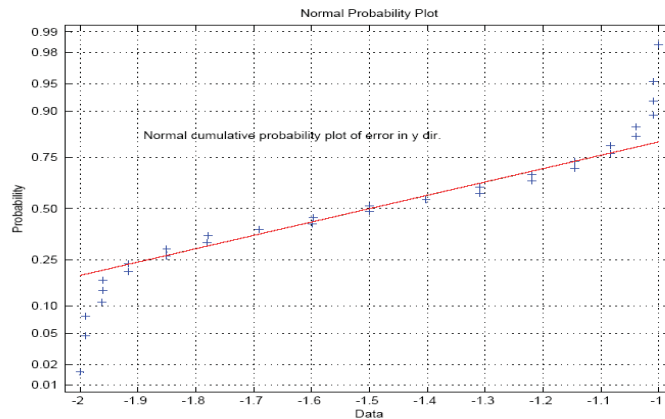


Fig. 26. Normal cumulative probability plot of error in x direction.

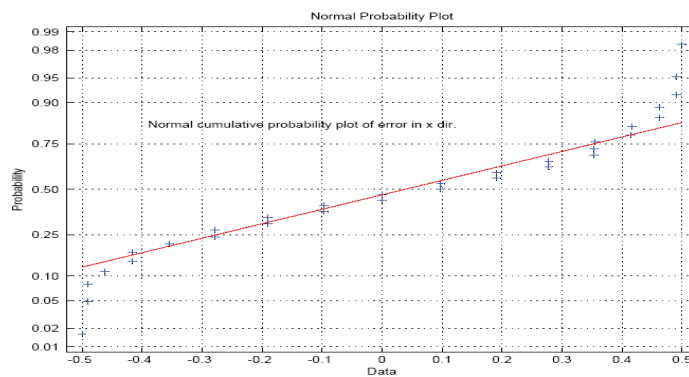


Fig. 27. Normal cumulative probability plot of error in y direction.

8. Conclusions

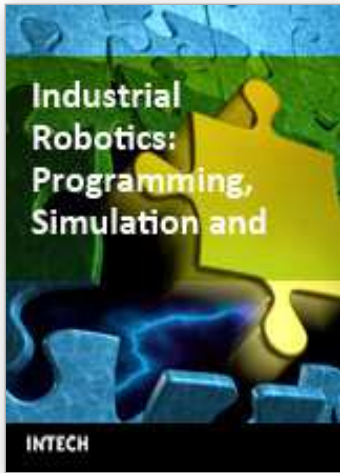
It has been shown how to use a vision system to control industrial 3P and 6R robots. It was observed that before using this vision system for controlling a robot, we need to know general information of the robot and the camera function and affects of light conditions on taken images. We can assume these results from the system as a better and more accurate control on robot around. In this system there is no need to know the first location of robot to calculate the required movement toward the goal, because taken images will help us to know the distance of the object to the end effector and this is one of the advantages of this system. Vision system can be used for path-related characteristics of robot. In this article, by applying vision system, the path-related parameters are found for industrial robot. The calculation of the path accuracy is simplified by finding the intersection of the attained path. Also simulator package for 6R robot, its different Sections and its capabilities are described. Control and performance tests for 6R and 3P robot have been simulated by using position based and feature based visual system. In position based visual system it is not necessary to know the initial position of target-object and end effector due to capability of the target pose estimation in this method. Direct and inverse kinematics equations of the 6R robot have

been simulated and three-dimensional information of the target and end effector by using two cameras with acceptable accuracy have been implemented.

Errors have been analyzed by using different standards and also MATLAB to compute performance parameters of 6R robot such as accuracy, repeatability, and cornering overshoot. According to ANSI standard maximum repeatability is $PR = 0.375$ and average repeatability is $\overline{PR} = 0.264$ and according to standard ISO9283 we had average repeatability equal to $\overline{PR} = 0.42$, they are fairly close to each other. Also MATLAB showed error data were fairly normally distributed with standard deviation equal to 0.353 and skewness of -0.184.

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Industrial Robotics: Programming, Simulation and Applications

Edited by Low Kin Huat

ISBN 3-86611-286-6

Hard cover, 702 pages

Publisher Pro Literatur Verlag, Germany / ARS, Austria

Published online 01, December, 2006

Published in print edition December, 2006

This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

M. H. Korayem, F. Heidari and H. Aliakbarpour (2006). Simulation and Experimental Tests of Robot Using Feature-Based and Position-Based Visual Servoing Approaches, *Industrial Robotics: Programming, Simulation and Applications*, Low Kin Huat (Ed.), ISBN: 3-86611-286-6, InTech, Available from: http://www.intechopen.com/books/industrial_robotics_programming_simulation_and_applications/simulation_and_experimental_tests_of_robot_using_feature-based_and_position-based_visual_servoing_ap

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