JCARME
ISSN: 2228-7922
Journal of Computational and Applied Research in Mechanical Engineering
Vol. 6, No. 1, pp. 11- 20, Aut.-Win. 2016-17
http://jcarme.srttu.edu

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Improvement of position measurement for 6R robot using magnetic encoder AS5045

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Article info:

Received: 11/01/2015
Accepted: 17/04/2016
Online: 11/09/2016

Keywords:
Magnetic sensors,
6R robot,
joint angle,
PD controller.

Abstract

Recording the variation of joint angles as a feedback to the control unit is frequent in articulated arms. In this paper, magnetic sensor AS5045, which is a contactless encoder, is employed to measure joint angles of 6R robot and the performance of that is examined. The sensor has a low volume, two digital outputs and provides a high resolution measurement for users; furthermore its zero position is adjustable. Installation and use of this measurement system on 6R robot has been expressed by using output signals of sensor AS5045 in the digital control board of 6R and equipped with ARM processor LPC1768. First, a sample of digital board is used for controlling a DC motor in both speed and position, in order to investigate specifications of AS5045's digital and analogue outputs. Simulation of 6R robot in point-to-point motion has been performed with MATLAB software using a proportional derivative (PD) controller. Then, experiment with the same condition and gains via a PD controller has been designed and implemented on the digital control board. The feedback system has been also checked in a circular path to show its advantages in trajectory tracking. The comparison of simulation results with experiments shows improvement: less error and better performance of 6R robot. This new setup omitted the noise of previous analogue feedback system since its digital outputs provides a precise measurement.

1. Introduction

The incremental counters provide the position and velocity information as a simple digital data with the minimum entry requirements. Design and construction of a gripper has been done using a DC motor and servo optical encoder [1]. In that design the optical encoder was attached to back of the motor. Same measurement system was used via an encoder for determining position of the gripper of system which is a spherical walking robot [2]. Composition of a five-axis kinematic chain was introduced by Kim et al. made of a three degree-of-freedom (DoF) parallel robot with a two DoF arm [3]. Encoders in the motor shafts were used to ensure high accuracy in the proposed design.

Despite the widespread usage of the incremental encoders, inefficiency of them to measure absolute position should be regarded.

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In order to solve this problem, combination of encoders with another device were used for determining the absolute position of the robot. Planning and designing the robot using multi-sensor scheme was proposed by Yuet al. [4]. The proposed method was combined information from various sensors in different temporal and spatial scales for controlling a robot. Combining the information of encoder sensors and visual measurement, the absolute position of the robot was obtained. Another way to reach an absolute position is to employ potentiometer to set origin of motion. Potentiometers provide information of absolute position; and its application is simple and affordable. Reemeijer used this approach to design and manufacture a robot's controller for pipe inspection in sea via incremental encoder for providing feedback of motor's speed [5]. Moreover, a potentiometer was used to measure the position and estimate the engine torque.

The robot with mechanism of an inverted pendulum was designed; possessed a T-shaped link connected to the main body [6]. The robot used a rotary joint to measure the angles of rotation by potentiometers. Wang et al. designed under actuated robotic arm which consisted of three fingers and a joint [7]. In that scheme potentiometers were applied in the joints to determine the position of the hand. Potluri et al. built a prototype of an artificial limb [8]. To estimate the joint angles and controlling the hand, adaptive method was used and the feedback benefited from potentiometers.

The main objection to potentiometers is the analogue output of them that forces the designer to use a microprocessor to convert it to digital data. However, in some applications, a counter and a potentiometer can be employed to provide the necessary information. Zagler and Pfeiffer introduced MORITZ which is kind of a creepy robot used in pipelines [9]. MORITZ was equipped with encoders for obtaining angular measurement and computed joint velocity. The advantages of using encoders were mentioned high accuracy and reducing the time of computation [9]. Quigley et al. tried to present an affordable measurement system in the design of a robotic arm with seven DoFs using encoder and potentiometer to determine the velocity and position of the joints [10]. Nasu et al. used the combination of a potentiometer and an encoder on a DC servo motor in the structure [11].

In selection of rotary encoders, some factors should be considered such as accuracy, speed or position control, stability, resolution, power consumption, bandwidth and other features. Accuracy of position measurement seems to be the most important item among the mentioned factors. Servo setup in various areas of industrial automation is frequently used such as automation of machine tools, productive machines, conversion, and handling of materials, printing, and robotics.

Digital sensors are preferred for compatibility with control systems. Generally optical types of digital encoders are clearly compatible with the control system since these sensors provide position information in digital form. Practical limitations of digital optical encoders were investigated with regard to the optimal usage [12]. A new method for the position measurement of a brushless DC motor was presented [13]. In that way Hall affect analogue sensors measured the magnetic field of the rotor's magnet and the absolute position of the motor was calculated. The advantage of this method was high precision and low startup cost. Another advantage of magnetic measurement method is its contactless structure. A mechanical coupling is needed in setting of optical encoders and potentiometers, which is sensitive to axial error in installation of it. The small axial misalignment is allowed by this contactless option when mounting the magnet on motor shaft is difficult.

In this article the measurement system of 6R robot has been improved to provide a precise feedback. The previous version of measurement system used potentiometers [14-15]. Although the previous systems have worked, but having better results and more precise system, the magnetic encoders were chosen to enhance the precision of the robot [16]; in this present article the details of this measurement system will be reviewed. Desbiolles and Friz developed the resolution of sensor element MPS40S which installed in over 50 million cars now by using

magnetic encoder [17]. Wang et al. worked on the development of a magnetic rotary encoder, which was applied to the windward system of offshore wind farms. The encoder was equipped with a magnetic sensor for detecting a rotary magnetic field's direction change in a non-contact way in order to meet the harsh requirements of the offshore platforms [18].
In Section 2, evaluation and assessment of the digital board of measurement system is expressed. Position control of a DC motor is described in Section 3. Section 4 introduces the 6R robot and its control structure. Results of experimental tests on a specified route point and a circular path are presented in Section 5. Section 6 also includes the interpretation of the results and conclusions.

2. Construction of joint angle measurement

2. 1. AS5045 magnetic encoder

AS5045 sensor is a contactless magnetic rotary encoder, Fig. 1, which is used for accurate angular measurement range of up to 360°. In the structure of this sensor which is built on a chip, Hall Effect technology and digital signal processing were employed. In order to measure the angle, chip and a simple dipole magnet at the center of the shaft are required. This magnet may be placed above or below the chip.

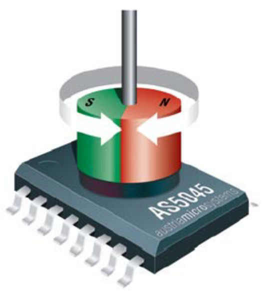

Fig. 1. Schematic of the magnet and the sensor [19].

Measurement of absolute angular position is available with resolution of 0.0875°. This amount is equal to one complete rotation per 4096 sections. Digital information of the calculated position is available in two categories: digital data and PWM signal. The bandwidth of the PWM signal is programmable in either way: micro-seconds per pitch (frequency 244Hz) or two micro-seconds per pitch (frequency 122Hz).
In Daisy Chain mode, multiple AS5045 sensors can be connected in a serial circuit. The sensors' data in a chain could be sent in a serial form from the output pin of the first sensor in the chain. Length of data will be increased by adding another sensor, and clock frequency is one MHz in the whole chain. The configuration of multiple sensors is illustrated in Fig. 2.
Sensor's operating voltage is set by voltage regulator at the value of 3.3 or 5 volts. Design and structure of circuits in the chip is in a way to minimize the noise. Therefore, the sensor will not require output filter; also in its structure thin film of resistors are used to increase and guarantee the stability of the sensor and the accuracy when the temperature changes. The sensor operating temperature is between -40 to 125°C which is appropriate for many industrial and general applications.

2. 2. Startup board of AS5045

The design and implementation of the driver board of encoder is formed to provide the access to all inputs and outputs and the ability to use the serial SPI outputs or PWM signal. The PROG pin is accessible for two state, each of them both Daisy Chain and programming are considered. A first-order low-pass filter is used to eliminate output noise of the encoder as the next option for PROG. Schematic picture of Design Circuit is presented in Fig. 3.
The new digital board could use either analogue or digital output which omits the noise which reduced the precision in previous potentiometer measurement system. Moreover, the absolute measurement is an advantage respect to incremental optimal encoders. The resolution is much higher than the old system.

3. Test on DC motor

3.1. Introduction to setup

To verify the authenticity and review the different aspect of AS5045, this board is set to measure the angular position of a DC motor as a benchmark problem. A special magnet on the motor shaft must be placed in front of the encoder with a specified distant (almost less than 2 millimeters). The setup is presented in Fig. 4.

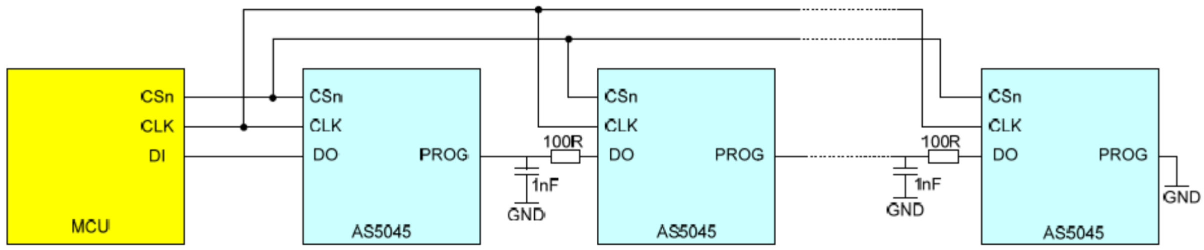

Fig. 2. Schematic circuit of Daisy Chain Mode and sensors in series contact [19].

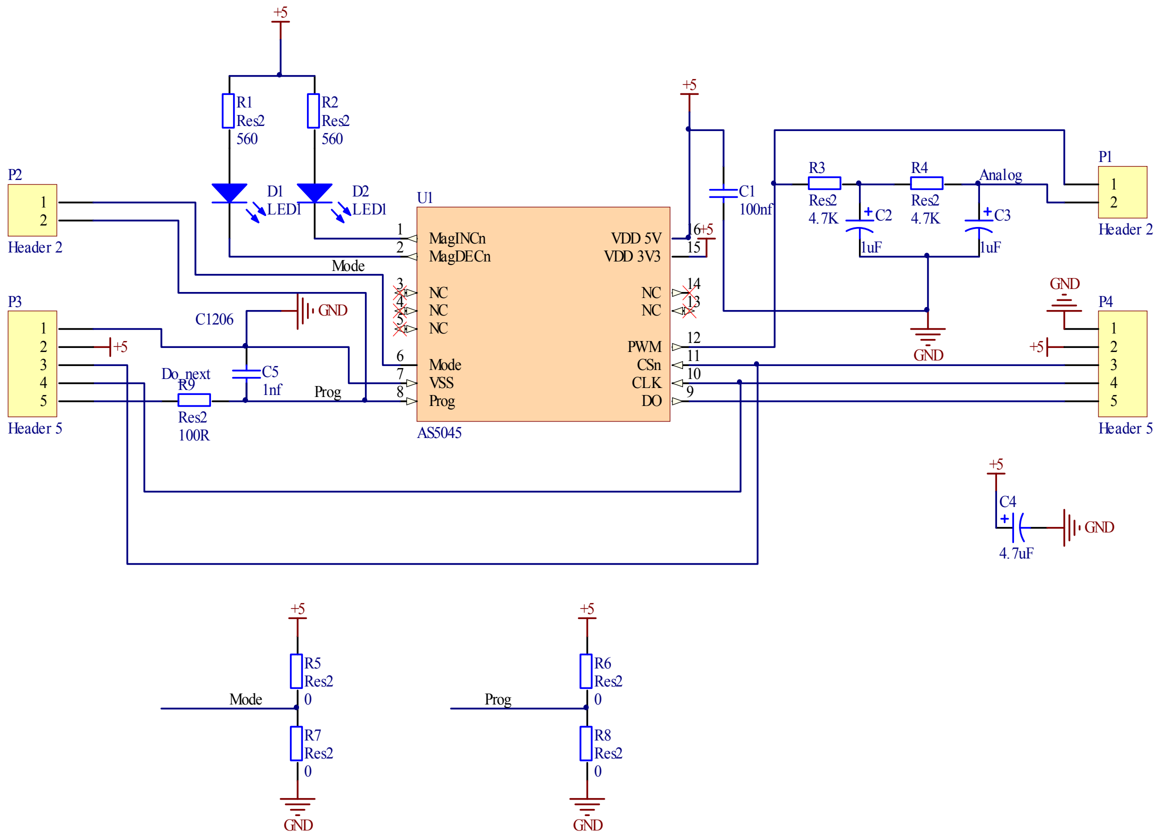

Fig. 3. Schematic of driver circuit of encoder.

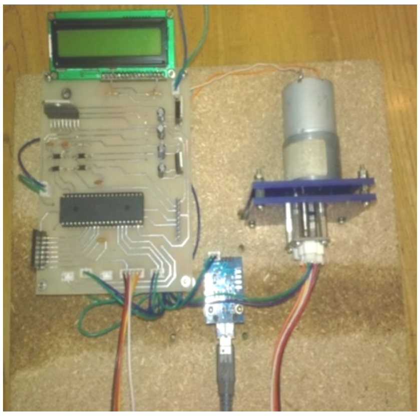

Fig. 4. Driver board mounted on a DC motor.

3. 2. Testing the position of the DC motor

The comparison of analogue and digital output signals of sensor was done on the experimental setup. In this experiment the motor was tested during start-up with different initial positions. The data was recorded in two different modes of analogue and digital signals in Fig. 5. The purpose of this experiment is to investigate the noise and precision of the analogue and digital outputs. Moreover, both analogue and digital outputs of encoder are shown together in the same figure for making a comparison.

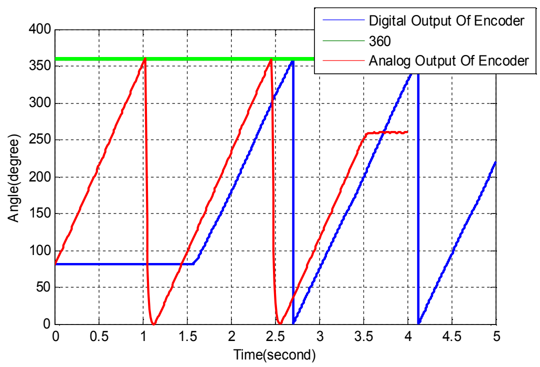

Fig. 5. Comparisons of digital and analog output signals of the sensor.

A PID control algorithm was implemented on the single DC motor; its results are demonstrated in Fig. 6. In this experiment, the desired angle was considered 168 degrees. The actual angular position of the controlled quantities for different speeds reached its final value properly.

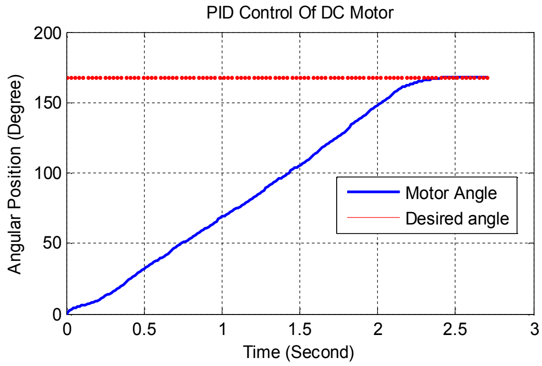

Fig. 6. Controlled DC motor using PID controller.

4. Introduction to 6R robot

In this section, 6R robot is briefly reviewed which is an industrial robot which has six DoFs; all the joints are revolute. Each of the six joints rotates independently by a DC motor connected to a gear box. 6R robot is shown in Fig. 7.

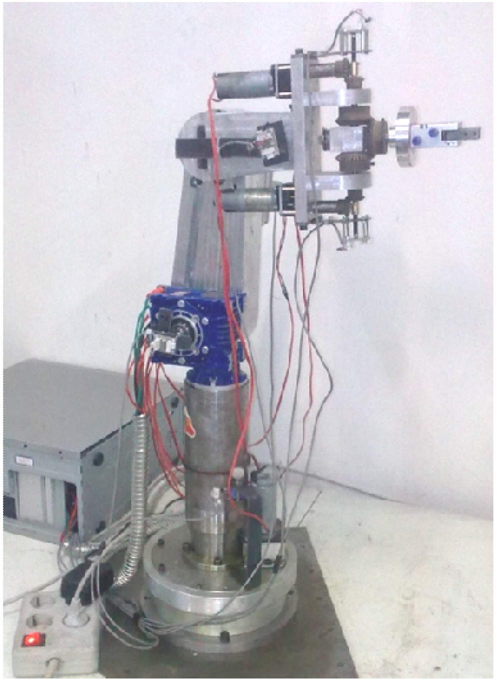

Fig. 7. 6R robot.

Geometric parameters of the robot in accordance with the definition of Denavit-Hartenberg are presented in Table 1; Robot geometry has been included in this table too. Considering the motion of the links as generalized coordinates $\mathbf{q}(t)=\{\theta_1(t),\ldots,\theta_6(t)\}$, a general form of dynamics equation of a robot, can be presented as:

$$\mathbf{M}(\mathbf{q}(t))\ddot{\mathbf{q}}(t)+\mathbf{C}(\mathbf{q}(t),\dot{\mathbf{q}}(t))+\mathbf{G}(\mathbf{q}(t))=\mathbf{u}(t), \quad (1)$$

where $\mathbf{M}(\mathbf{q}(t))$ is the inertia matrix, $\mathbf{C}(\mathbf{q}(t),\dot{\mathbf{q}}(t))$ is the vector consists of terms due to the centrifugal and Coriolis force, $\mathbf{G}(\mathbf{q}(t))$ the gravity force and $\mathbf{u}(t)$ the input torque. The state vector is selected as:

$$\mathbf{x}(t)=[\theta_1(t), \ \ldots, \ \theta_6(t), \ \dot{\theta}_1(t), \ \ldots, \ \dot{\theta}_6(t)]^T. \quad (2)$$

Therefore, the state space representation of the system is formed as in the following:

$$\dot{\mathbf{x}}(t)=[x_7(t),\ldots, x_{12}(t), \mathbf{M}^{-1}(\mathbf{x}(t))\big(\mathbf{u}(t)-\mathbf{C}(\mathbf{x}(t))-\mathbf{G}(\mathbf{x}(t))\big)]^T. \quad (3)$$

Table 1. The Denavit-Hartenberg parameters of 6R.

Joint number	a_i(mm)	d_i(mm)	α_i(°)	θ_i	Motion
1	0	438	-90	θ_1	Link 1
2	251.5	0	0	θ_2	Link 2
3	125	0	0	θ_3	Link 3
4	92	0	90	θ_4	Link 4 (Yaw)
5	0	0	-90	θ_5	(Pitch)
6	0	152.8	0	θ_6	(Roll)

The necessary torque for motion of the link is provided by DC motor. The specifications of motors are presented in Table 2.

Table 2. The stall torques and no-load speed of the motors [20].

Motor	1	2	3	4	5	6
U_{stall} (N.m)	114	98	382.2	40.4	40.4	40.4
ω_{stall} (rad/s)	1.3	1.04	0.73	0.9	0.9	0.9
Gear box ratio	1:333.2	1:100	1:500	1:500	1:500	1:500
Voltage (v)	12	24	12	12	12	12

BTS7810 drivers were used to provide the necessary power to run the motors. The side view of the robot is presented in Fig. 8. The large view of the mounted encoder along with its digital board is presented in Fig. 9.

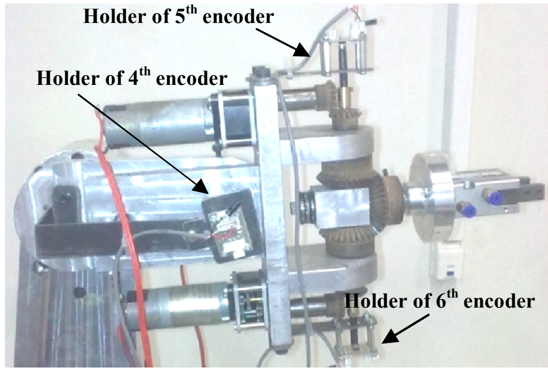

Fig. 8. The side view of the robot.

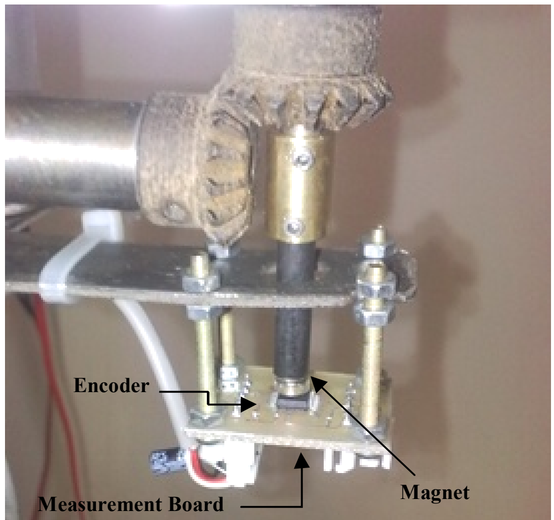

Fig. 9. Detailed view of encoder on the 6th link.

5. Experimental tests on 6R

5. 1. The point-to-point motion

The start point is $A(0.574,0,0.748)$ and the end point is $B(0.076,-0.620,0.375)$. Initial condition and desired states using inverse kinematics of 6R for point-to-point motion are presented as:

$$x(0)=\left[0,-0.52,0,0,-1.57,0,0_{1\times 6}\right]^T, \quad (4)$$

$$x_{des}(t_f)=\left[-1.57,0,0.52,-0.52,-1.04,0,0_{1\times 6}\right]^T. \quad (5)$$

The point-to-point motion is presented Fig. 10. The time of simulation was set three seconds. Error in each arm was calculated online in the movement every 20 milli-seconds and according to coefficients of a PD controller that was designed for each motor, in the following equation:

$$u_i = -k_p(\theta_i(t) - \theta_{des,i}) - k_d(\dot{\theta}_i(t) - \dot{\theta}_{des,i}), \quad \text{for} \quad i = 1,\ldots,6 \tag{6}$$

where k_p is proportional coefficient and k_d in derivative coefficient. The desired values in point-to-point motion are constant. Unfortunately, due to the physical limitation in this experimental platform, it has not been easy to measure the velocity level of point-to-point motion since sensors could not provide them, however, the velocity level of point-to-point was computed by numerical calculation.

Then the PWM of each motor is computed and sent to BTS7810 drivers. The angles of links are presented in Fig. 11.

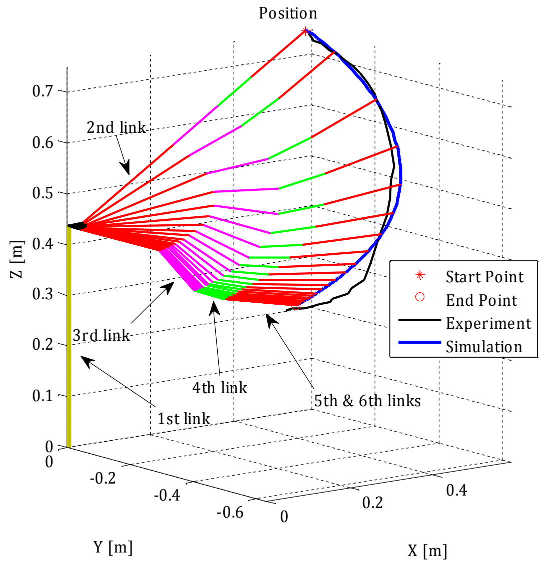

Fig. 10. Point-to-point motion of the arm and configuration of the links.

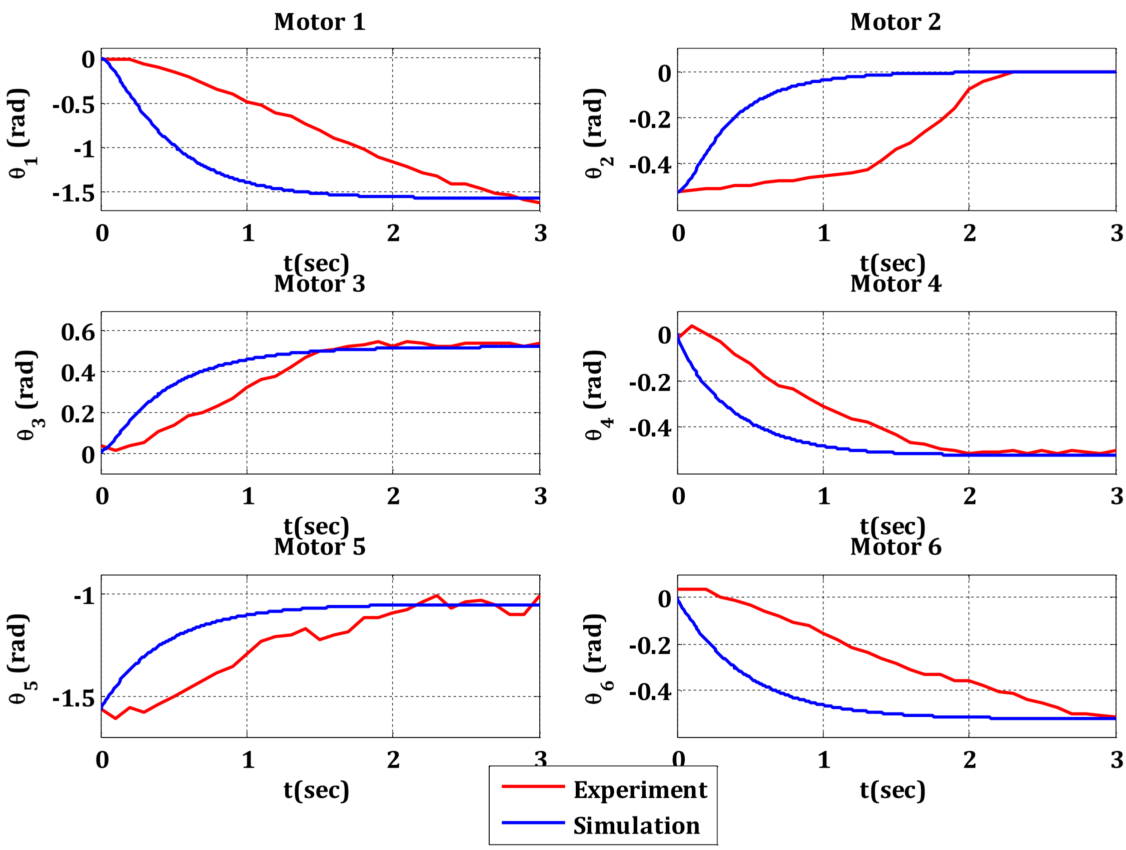

Fig. 11. Angles of links in point-to-point motion.

5. 2. Trajectory tracking

In this section, the robot is simulated in a circular path, trying to track the desired trajectory. The equations of path are as follows:

$$x_e(t) = 0.05\cos t + 0.46, \tag{7}$$

$$y_e(t) = 0.1\sin t, \tag{8}$$

$$z_e(t) = 0.05\cos t + 0.56. \tag{9}$$

The required time for the proposed trajectory is 2π seconds, but the 50 selected points for tracking the whole path are to convey in almost 2.5 seconds. In this motion, a PD controller was used. The motor of the second link is a little weak respect to the weight it should handle. Therefore to gain better results it was fixed. The trajectory is divided to 50 points for the controller to track each of them in its limited time. Figure 12 shows the resulted variation of angles. The actual and desired trajectories with configuration of links are shown in Fig. 13. The error of trajectory tracking is presented in Fig. 14.

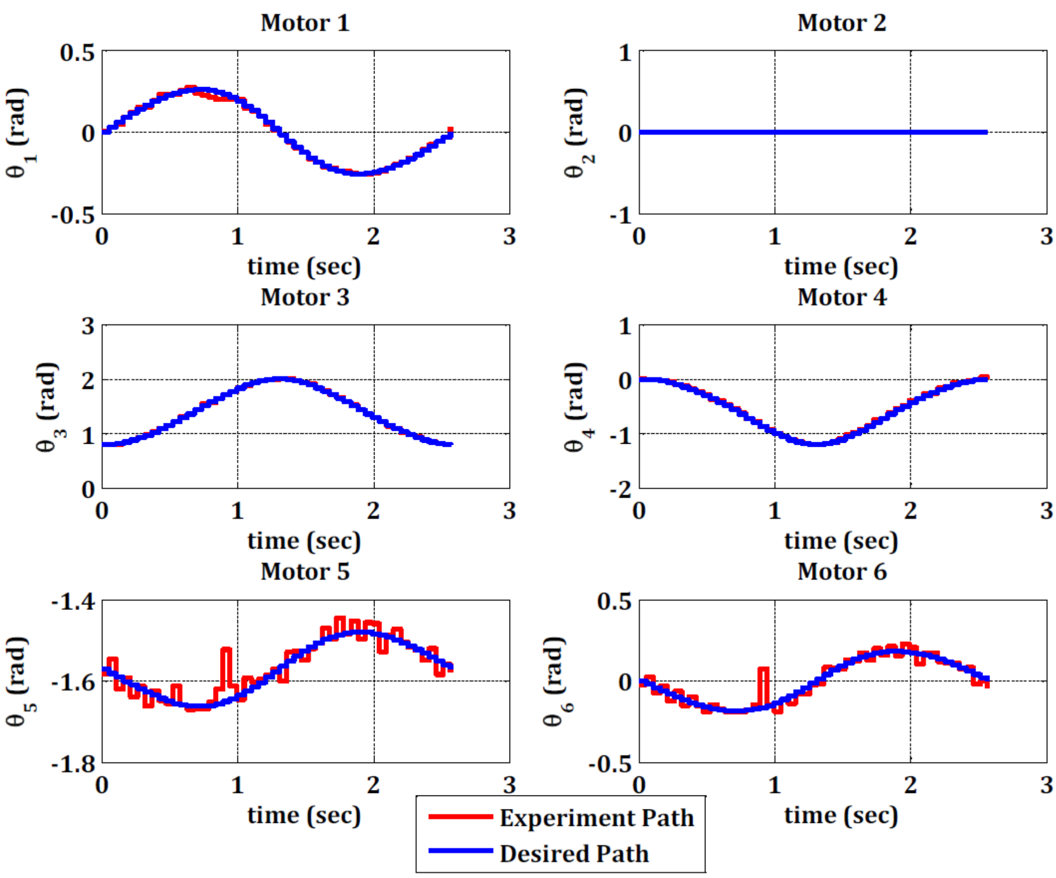

Fig. 12. Angles of links in trajectory tracking of 6R: circular path.

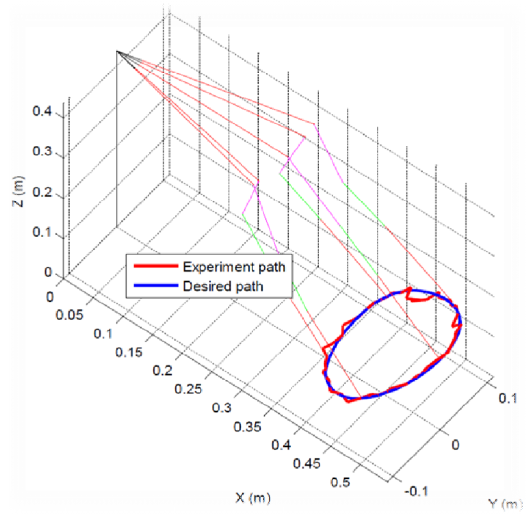

Fig. 13. Position and configuration of 6R robot in 3D space: trajectory tracking.

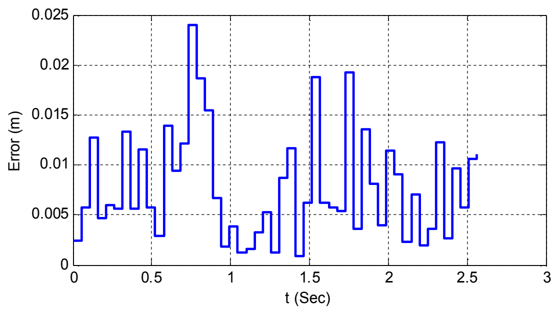

Fig. 14. Tracking end-effector error in circular path.

6. Interpretation of results and Conclusions

The position measurement accuracy of the robot for carrying out the tests in point-to-point motion was investigated for the two measurement setups: potentiometers and encoders. Replacing the magnetic encoders on 6R robots increased the accuracy of the arm. The points and parameters of the PD controller for comparing the results were the same. Table 3 shows the results of the tests in two modes. Unfortunately, the results of that specific trajectory were not available by potentiometer measurement system, so the summation of error in 50 points and the average of error are presented in Table 4.
In this paper, the AS5045 magnetic encoder was used to measure the position of the 6R robot using ARM microcontroller, based on PD control algorithm. The replacement of magnetic encoders was improved speed and accuracy in the measurement of 6R robot rather than potentiometers used in the previous version.

Table 3. Comparing test results point-to-point motion.

State	Position sensor	Position error of end effector
1	potentiometer	41 mm
2	Magnetic encoder	24.4 mm

Table 4. Results in tracking.

Sum error of end effector in 50 point	Average error of end effector in 50 point
394.1 mm	7.882 mm

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