Design and Implementation of Rehabilitation Robot for Human Arm Movements †

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Abstract – Physical disabilities such as full or partial loss of function in the shoulder and elbow are a common impairment in the elderly and a secondary effect due to strokes, trauma, sports and injuries. Rehabilitation programs are the main method to promote functional recovery in these subjects. This work focuses on designing and implementing a 3 DoF's non-wearable, light weight rehabilitation robot for rehabilitee the human arm that can be used in hospitals or homes. This robot structure eliminates arm singularity problem of the end effecter with respect to the robot base by adding an offset link. The design includes an adjustable mechanism standing on a seat for robot base and links to be adaptable for all body sizes and to align for all human arm lengths.

Intelligent PD-like Fuzzy Logic position controllers (FLCs) are designed for joints of the 3 DoF's robot to follow the desired medical trajectories during limited time with minimum overshoot and minimum oscillations in position response. These controllers are implemented using MATLAB Simulink. The controllers control the rehabilitation robot using Data Acquisition Card, (Advantech PCI-1712) that generates and reads the required digital and analog signals for robot. The experimental results are acceptable in terms of the practical application.

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Keywords – Position control, Rehabilitation robot, Intelligent controller, Arm movements, Medical trajectories.

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1. Introduction

Rehabilitation programs depend on robotics technology and other medical processes for rehabilitee. These programs are used for therapy of the people who have been suffering from injuries in the nervous system, stroke, traumatic brain injury and sport injury [1]. What is Stroke? Stroke is the result of supplying blood to the part of the brain which is suddenly interrupted away or when bursts the blood vessel in the brain spilling blood into the spaces surrounding brain cells. The injuries cause movement disorders, such as muscular weakness, loss of muscle coordination, and the consequent inability to perform elementary functional tasks of limbs, such as eating and gripping objects like food or cup catching. This makes activities of daily life so hard for patient with stroke [1].

Rehabilitation program can improve long therapy section to recover injury person limb ablates. So, if the therapy starts at short time as possible after injury, the activation of rehabilitation program will be better and faster that include highly repetitive movements training. The rehabilitation program should be performed by therapist. The drawback in the method of treatment is the incorrect therapeutic movements which result in fatigue therapist during the treatment. This could lead to a negative impact on the injured person. Here comes the role of the robot, which leads movements consistent and repeated tirelessly or fatigue that can be used in hospital or at home. It assists in training and many patients can work with it daily [1]. The rehabilitation robots those which designed previously are Nefand Riener who designed in 2005 a 6 DoF's to work with shoulder and elbow joint for arm therapy [2]. Perry, Rosenand Burns proposed in 2007 segments that work with shoulder, elbow, wrist joints and forearm motion 7 DoF's rehabilitation robot that having brushed motors torque transferred by Cables [3]. Furthermore, Rahman, Saad, Kenné, and Archambault, Rahman proposed in 2009 a 7 DOF's rehabilitate robot for therapy patients. The modeling of forward kinematics is done by DH convention. A PID torque controller was designed by utilizing the equation of motion. High Initial torque problem was solved by interpolation function [4]. Xianzhi, Caihua, Ronglei and Youlun designed in 2010 a hybrid Force-Position controller using fuzzy Logic for the robotic arm of9 DoF's human arm wearable rehabilitation robot [5].Ozkul and Barkana designed in 2011 an admittance control with inner robust position control loop to provide the necessary motion to rehabilitee, so patients can complete the rehabilitation tasks in a desired manner [6]. Stiffness and impedance control concepts proposed by Mehdi and Boubaker in 2012 to solve position and force control for robot-aided rehabilitation [7].

In this work, a 3 DoF's non-wearable rehabilitation robot (2 DoF's for shoulder motions and 1 DoF for elbow motion), is designed and implemented using electric type brushed DC motors with gearbox as actuators. The singularity problem; that comes from the alignment of the end effecter in the Z-axis direction with the base Z-axis makes the robot faces infinity solutions for first joint angle. This problem can be solved by adding shoulder offset that cover the change in the shoulder center through motion. Furthermore, the center of rotation of the shoulder is overcome by adding a fixed link that join first and third link of the arm to move in parallel with shoulder. PD-like FLC position controllers are designed and implemented using Matlab Simulink to control the robot links. The control signals generated from simulink are supplied through interfacing circuits to the actuators using data acquisition card (Advantech PCI-1712). Also, the interfacing circuits between the card and the robot are reading the motor shaft encoders using digital input signals and supplying analog output control signals to drive the motors to the desired position. The proposed robot structure is fitted on a seat that having adjustable mechanism to align different human body sizes.

2. Design of the rehabilitation robot

The design of the proposed rehabilitation robot is divided into four groups; seat structure, robot links, singularity problem solution, interfacing circuit and PD-like FLC Position controller.

2.1. Seat Structure Design

The non-wearable rehabilitation robot structure should stand on a seat or a mechanism to enable the injury person getting the comfortable and correct position through the training term. The proposed structure of the seat with the robot is shown in Fig. 1. It can be noticed from this Figure that the robot structure standing on an adjustable mechanism that is located on the back of the seat. Furthermore, the seat is made from stainless steel rectangular bars for a strong and solid structure to carry different weight soft human body and be resistant to rusty; see Figure 2. The dimensions of the seat and the robot structure are shown in Figure 3. Moreover, Figure 4 shows the designed mechanism on the seat back.

This mechanism can slide along Stainless Steel bars through a Stainless Steel bushes touching them. The structure consists of 3 bars. The horizontal motion is done by passing two bars through two horizontal bushes that can slide on the bars in the left and right direction. The third bar is a vertical one passing through a vertical two bushes that stand on horizontal bushes for up and down motion.

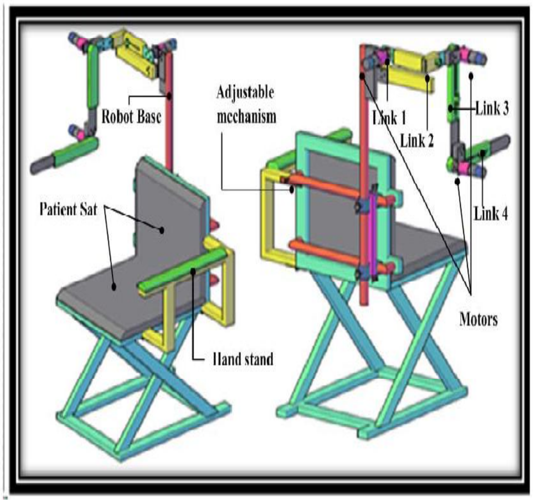


Figure 1. The proposed structure for the seat and the robot.

Figure 2. Views of the seat structure.

The base of the robot structure is located on the tip of the vertical bar that aligned vertically to the mechanism. These mechanisms have been aligned for all human arm sizes by moving the robot into different directions. Also, the seat includes belts to hold the injured person during the treatment term. In addition, the sides of the seat were made from wooden covered by sponge of high pressing and leather of high durability. Also, the seat includes a side stand for left limb that can open and close according to the needs.

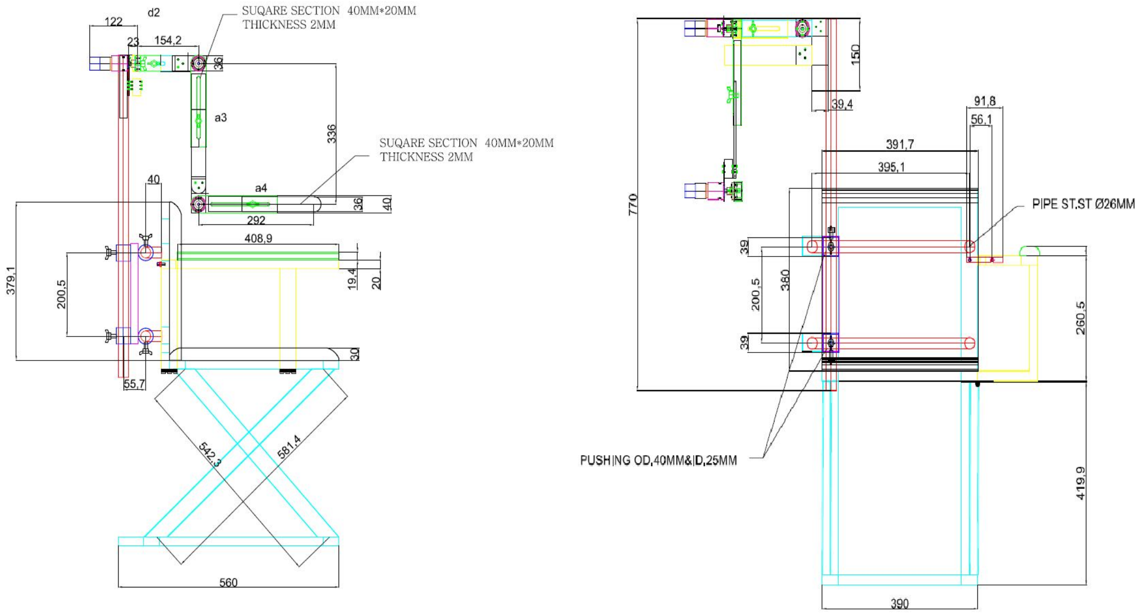


Figure3. Dimensions of the seat and robot structure

2.2. Robot Links Design

The design of rehabilitation robot links depends on Aluminum metal. The use of aluminum of rectangular shape is for its light weight that should be considered in robot links design. Fig.5 shows the robot links design that include lots for inter leaving two parts of links together. Each link consists of two parts; the first one is a rectangular hollow bar that is connected to one end of the motor and the second part is a sold bar of rectangular shape that is interleaved into the hollow part to make each link adjustable.

Figure 4.Views of the adjustable mechanism.

Only the first and second links are joined together by fixed joint without motor and oriented by 90 degree between them. Table 1 shows the lengths of each link of this design and Fig. 6 shows the overall robot structure with the seat.

Figure 5. (a) The robot base. (b) The first and second links. (c) The third link. (d) The fourth link. (e) Motors bases, Flanges and other finishing's.

Table 1.Robot lengths of links

Link	Minimum length (m)	Maximum length (m)
First link	0.16	0.235
Second link	0.15	0.225
Third link	0.255	0.39
Fourth link	0.215	0.37

Figure 6.Overall mechanical systems.

2.3. Singularity problem and its solution

In this work, the singularity occurs at configuration of end effecter with the base of robot. This configuration is similar to the articulated configuration 3 DoF's, as shown in Fig 7.

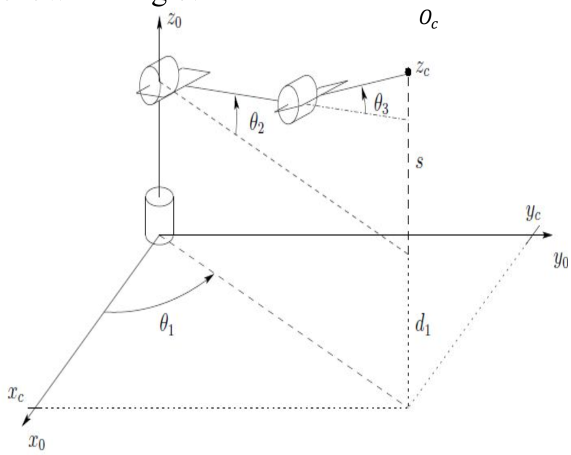


Figure 7.Articulated configuration of 3 DoF's.

Where x_c, y_c and z_c are the end-effecter coordinates frame at O_c and Θ_1 calculated through geometric approach by:

$\Theta_1 = atan2\ (x_c, y_c)$ (1)

The solutions for Θ_1 are valid unless ($x_c = y_c = 0$). In this case, equation (1) is undefined and the manipulator is in a singular configuration, shown in Fig 8. In this position the end effecter O_c intersects Z_0; hence any value of Θ_1 leaves O_c is fixed. There are thus infinitely many solutions for Θ_1 when O_c intersects Z_0.

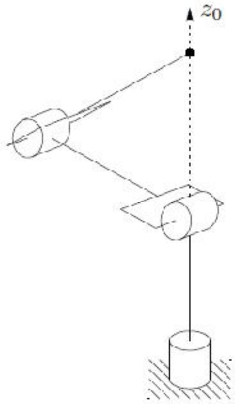


Figure 8. Singular configurations

By adding an offset (d≠0) as shown in Fig .9 then the wrist center cannot intersect Z_0. In this case, depending on how the DH parameters have been assigned, we will have (a1 = d). Fig. 10 shows the robot configuration that including the offset (d).

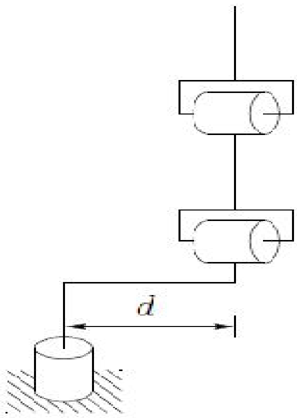


Figure 9. Manipulator with shoulder offset.

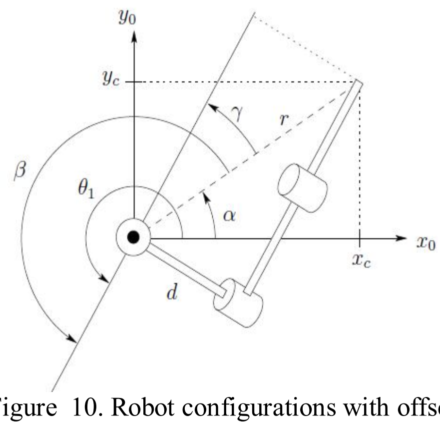


Figure 10. Robot configurations with offset

The mathematical solution for Θ_1 including offset is:

$\Theta_1 = atan2\,(x_c, y_c) + atan2(-\sqrt{r^2 - d^2}, -d)$ (2)

Where:

$r^2 = x_c^2 + y_c^2$ (3)

$\Theta_1 = \alpha + \beta$ (4)

$\alpha = atan2\,(x_c, y_c)$ (5)

$\beta = atan2\,(-\sqrt{r^2 - d^2}, -d)$ (6)

2.4 Interfacing Circuit Design

The interfacing circuit is needed for transferring the control signals from the simulink model in the computer to the physical robot actuators, (brushed DC motors with gearbox; one motor of rated current 6 Amp for first joint and two other motors of rated current 1 Amp for other joints). The circuit is used to read the position sensors (incremental shaft encoders) that located on the back of the motors shafts. It was designed with minimum hardware requirements. A data acquisition card, Advantech PCI-1712, is used to interface the PC with the interfacing circuits. It is plugged on one of PCI busses of a PC. This card has 16 single-ended or 8 differentials of the combination of analog inputs, two 12-bit analog output channels with continuous waveform output function, 16-chanal digital inputs; 16-chanal digital outputs, and many other features [8]. A pulse width modulation signal of 3.3 KHZ is supplied to the DC motors drivers (L298 for 1Amp motors [9] and MD10C for 6 Amp motor [10]). These drivers can drive each motor with 12 volt supply voltage.

The reading circuits are designed according to the resolution of the shaft encoders that connected to the back of the motors. Figure 11 shows the hardware design of the driver and the counter circuits. For the 1 Amp motors that have sensor resolution of the 1848 pulse/rotation, they need 1024 bit counter circuits. Also, the 6 Amp motor that have sensor resolution of the 18850 pulse/rotation, it needs a 32786 bit counter circuit.

The minimization is done by using electric actuator with its interfacing electronics instead of pneumatic one as in [11]. Also, the minimizations in the driving circuits are done by using TL494 IC for pulse generation (PWM), [12]. These pulses used as inputs to the motor drivers. The 74LS194 IC counter is used for direct counting from the encoders in the read circuits. Fig. 12 shows the setup circuits connected to the Advantech PCI-1712 card. Moreover, Figure 13 shows the overall system of robot.

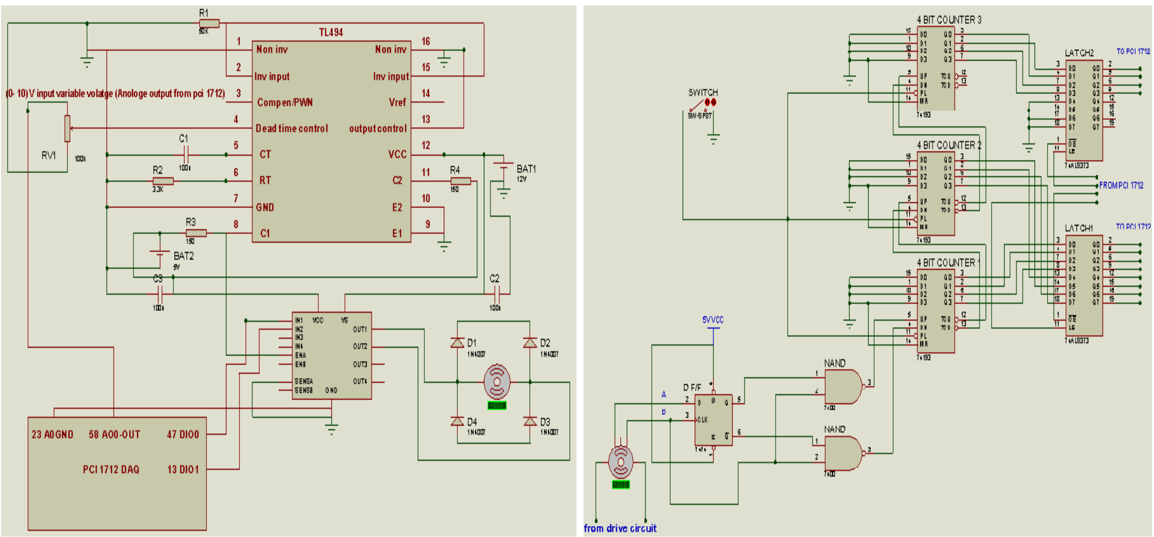


Figure11. The drive circuit motors (left) and the read circuit for each motor (right).

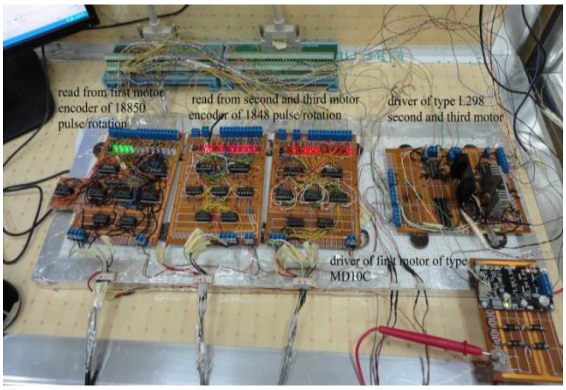


Figure 12. Interfacing circuits.

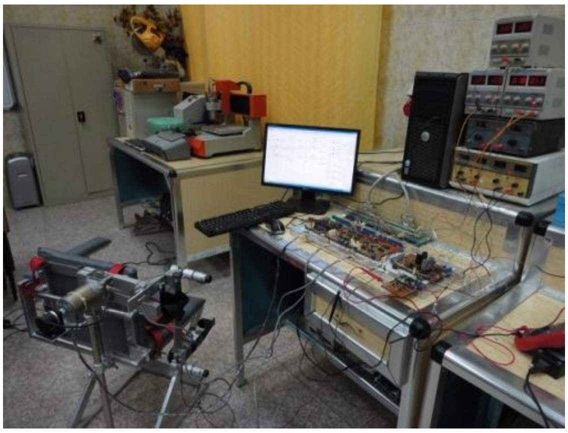


Figure 13.The 3 DoF'S rehabilitation robot

2.5. PD-like FLC Position Controller

The PD-like FLC is designed to control each joint position of the rehabilitation robot and it's built by using Matlab simulink. The FLC controller used to deal efficiently with the nonlinearities in robot and tracking the desired trajectories with minimum overshoot and minimum oscillations. The controller equation is:

$$u(t) = K_p e(t) + K_v \dot{e}(t) \qquad (7)$$

The inputs to the FLC are e (t) is the error signal and ė (t) is change of error. The K_p and K_v are the error and change in error gains and K_o is the output gain used to adjust the outputs membership range. The FLC is of Mamdani type. The inputs and output membership functions are seven triangles shaped. The defuzzification mechanism is selected to be Centre of gravity method [13].

Figure 14 shows the membership functions of the inputs and output and Table 2 lists the rules of the PD-like FLC Position controllers that were chosen by trial and error.

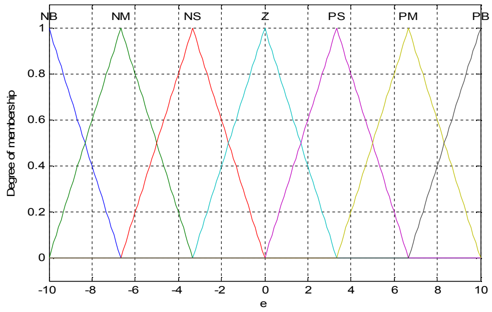


Figure14. I/O Membership functions of FLC

Table 2. FLC rules table.

ė / e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

The linguistic variables of FLC are NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The simulink model of the PD-like FLC connected with Simulink's blocks of PCI-1712 is shown in Fig. 15.

3. Results

The desired position trajectory that is applied is (90 sin (wt)) as an input for each joint. Fig. 16 shows the results of the desired and actual position response for each joint, including the PD-like FLC control signals and the error in position. The Root Mean Square Error (RMSE) is used as a measure of the match between the reference and the actual position responses. The RMSE values are shown in Table 3.

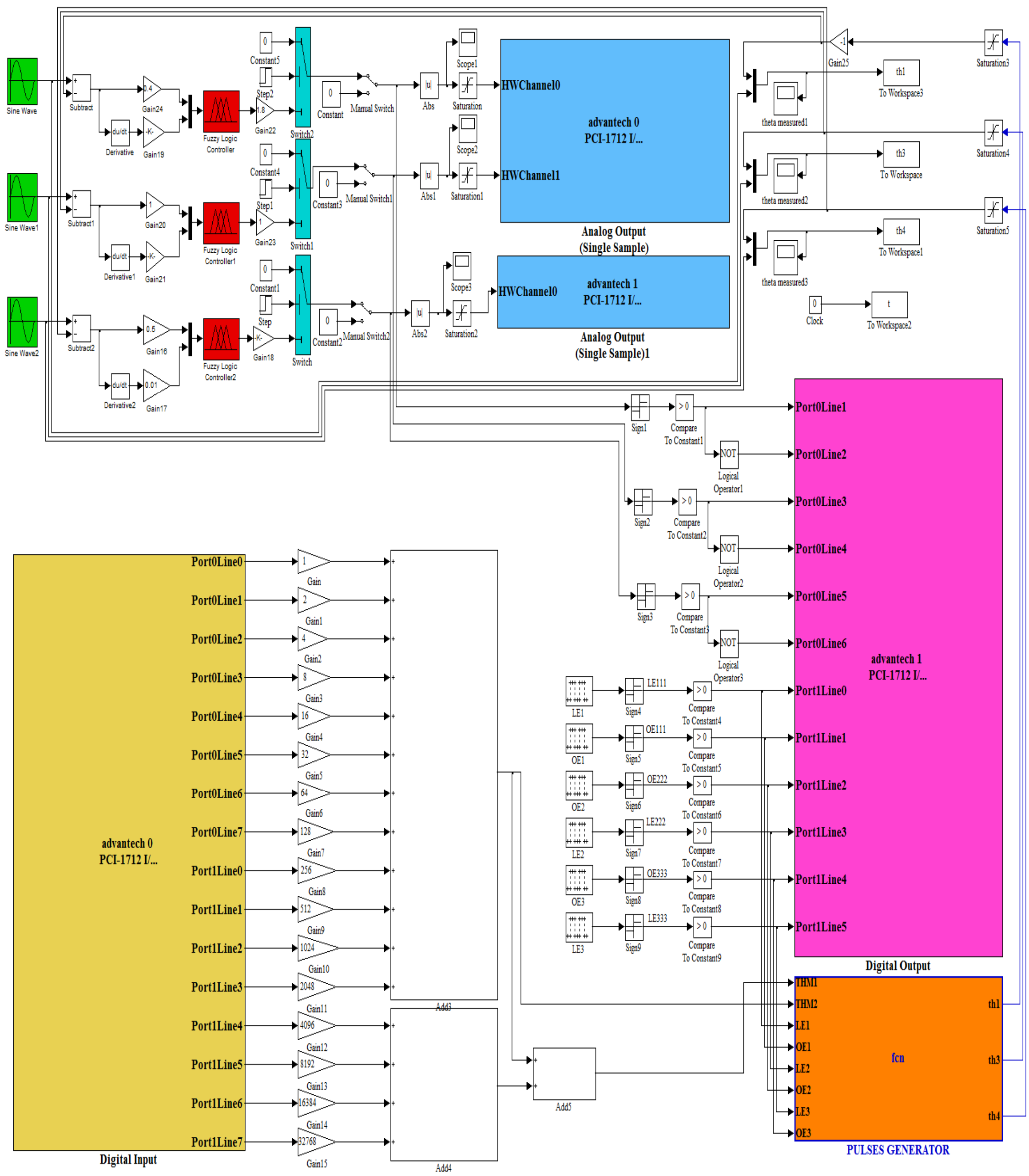
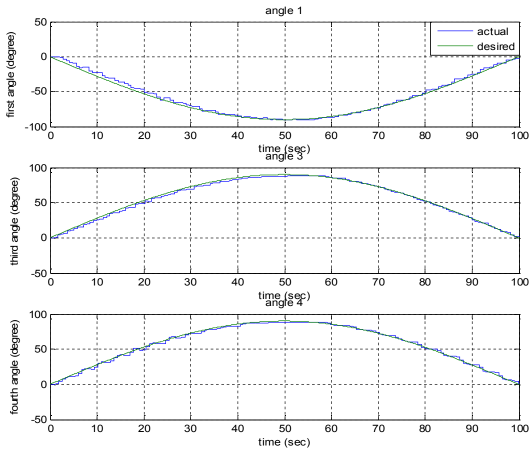


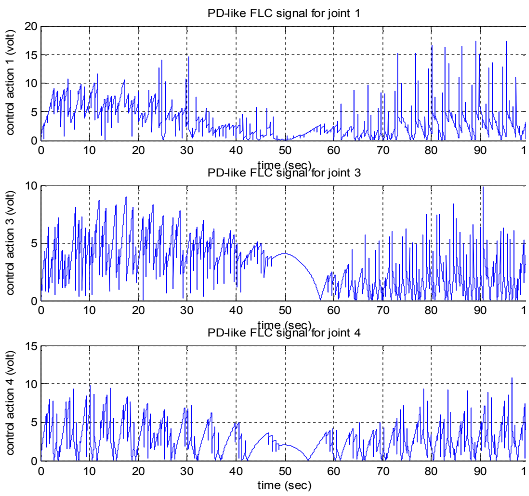
Figure 15. Simulink model of PD-like FLC with PCI-1712 I/O blocks.

Table 3 The Root Mean Square Error in each joint.

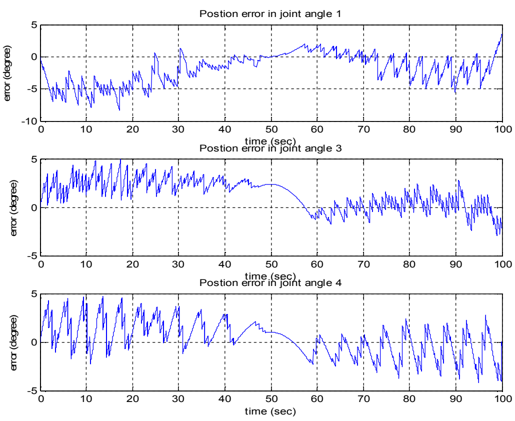
Joint	RMSE (Degree)
First	4.3567
Third	2.0647
Fourth	2.9928



(a)



(b)



(c)

Figure 16. (a) Position trajectory response, (b) Control signals and (c) Position error

4. Conclusions

It can be noted from the results that the actual response of the robot in each joint tracks the desired one with minimum overshoot and minimum oscillation movements. So, the values of RMSE shown in Table III are acceptable values. The errors in position are physically acceptable because; in the human arm training there is no need for so accurate responses. These errors come from the delay time in execution that existed in the simulink process and by the noise that came from the driving signals of motors and the resolution of encoders. The hardware minimization is another important point that was achieved by the proposed design of the interfacing circuits. The minimization in hardware for this robot design leads to minimization in cost. So, the patients can use it at hospitals or homes to exercise the medical trajectories without need for therapist. As developments to this work all simulink programs can be converted to executable files and saved in standalone devices to work faster and minimize hardware without the need to work under Matlab environment.

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