Modeling and Force-Position Controller Design 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, elbow or wrist is a common impairment in the elderly, and can also be a secondary effect due to strokes, trauma, sports injuries, and occupational injuries. Rehabilitation programs are the main method to promote functional recovery in these subjects.

This work focuses on designing and nonlinear modeling of 3DOF non-wearable rehabilitation robot for rehabilitee the upper limbs in human body. The structure of this robot will eliminate singularity problem by depending on articulated configuration through adding shoulder offset to the robot base. The nonlinear modeling of a rehabilitation robot including kinematic and dynamic models is done for three degrees of freedom, with the effect of friction term in robot actuator.

Three Intelligent Force-Position controllers, PD-like Fuzzy logic controllers are designed for position control and P controllers for force control, for moving the shoulder and elbow joints of the rehabilitation robot at desired trajectories. These controllers were tuned in order to make the robot end effecter tracking the desired medical trajectories in a specific time with minimum overshoot, minimum settling time and minimum steady state error. Each controller is tested by applying different trajectories with the application of external disturbances on the robot body.

A comparison between the proposed intelligent controllers and conventional PD Force-Position controllers shows superior of the intelligent type of controller to make the end effecter follow the desired trajectory compared with the use of conventional controllers.

Keywords: Force-position control, Fuzzy controller, Rehabilitation robot, Intelligent Control, Robot dynamics.

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نمذجة وتصميم مسيطر قوة ومسارلروبوت إعادة التأهيل الطبي لحركات الذراع البشرية

الخلاصة

الإعاقات الجسدية مثل الفقدان الكامل أو الجزئي لوظيفة من الوظائف في الكتف أو الكوع أو الرسغ هو ضعف شائع في كبار السن، ويمكن أيضا أن يكون لها تأثير ثانوي بسبب الجلطات الدماغيةوالصدمات النفسية والإصابات الرياضية . إن برامج التأهيل الطبي هي الوسيلة الرئيسية لإعادة فعالية الحركة للاطراف المصابة بالضعف الحركي.

يركز هذا العمل على تصميم روبوت طبي يتكون من ثلاث مفاصل يستخدم لإعادة تأهيل الاطراف العليا للجسم البشري (الذراع). حيث أن هيكل هذا الروبوت صمم لحل مشكلة تمييز نهاية المحوربالنسبة للقاعدة بالاعتماد على الروبوت المفصلي التكوين, وذلك من خلال إضافة كتف (ازاحة) إلى القاعدة . وضعت نماذج رياضية غير خطية لهيكل روبوت إعادة التأهيل متمثلة بنموذج الحركة الديناميكية ثلاثي المفاصل.وقد اخذت مشكلة الاحتكاك الموجودة في علبة تروس محركات المفاصل الكهربائية في التمثيل الرياضي لغرض السيطرة عليها . وصممت مسيطرات قوة وموقع تتضمن مسيطر منطق ضبابي ذكيمتناسب- متفاضل لكل محور للتحكم بمساره حسب المسار الطبي المطلوب ومسيطر متناسب- متفاضل للقوة . واختبرتالمسيطراتالمصممة الثلاثة من خلال تطبيق مسارات طبية مختلفة مع وجود الاضطرابات الخارجية على جسم الروبوت. وقورنت نتائج المسيطر المقترح مع مسيطرتقليدي وقد ظهر ان شبه الخطاء في استقرار الحالة في اتباع المسارات من قبل الروبوت قد قلتمقارنة مع أستخدام المسيطر التقليدي وكما هو موضح في نتائج البحث.

INTRODUCTION

Robotics are using in rehabilitation programs and many other medical processes. Rehabilitation program is used for therapy the persons who have suffering from injuries to the nervous system, stroke, traumatic brain injury and sport injury [1].

What is Stroke? Stroke is the result of supplying blood to 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. One of the most common disabilities resulted from stroke is Hemi paresis (One-sided paralysis), where the opposite side of the brain is damaged by stroke and may affect the face, an arm, a leg, or the entire side of the body [2]. These 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, gripping objects like food or cup catching. This makes activities of daily life so hard for patient with stroke [1].

Rehabilitation program can be improved by 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 movement training. Although 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 for assisting in training and many patients can work with it at daily [1].

Several rehabilitation robots were designed for working with human upper limbs. The robot geometry was designed according to limb segments that work with it; like Mulas rehabilitation robot which was designed for Hand segment. Furthermore, Perry and Rosen 2 DOF's rehabilitation robot was designed for Shoulder, elbow, wrist joints and forearm motion. Gupta is also a 7DOF's rehabilitation robot, for Elbow, wrist joints and forearm motion [3].Singularity problem is found in the rehabilitation robot according to its geometry and limits and needs solution with each design[4].Friction term and external disturbances are not included in robot dynamics. This makes the robot model less accurate [2 and 5].Controlling methods that are using in rehabilitation robot are facing design problems; like finding sliding surface in [5].Reaching accurate position response is another problem when including friction or disturbance in robot dynamic model, especially when using conventional controllers [2] [6].

In this work, a 3 DOF non-wearable rehabilitation robot is designed and modeled non-linearly. The friction phenomenon in robot joints is added and singularity problem is solved by adding shoulder offset. Furthermore, the center of rotation of the shoulder is overcome by adding fixed link that join first and third link of the arm, to move in parallel with shoulder. Force-position Fuzzy Logic controllers are designed to control the links of the robot.

The proposed robot structure is fitted on a seat that having special adjustable mechanism for alignment of different human body sizes.

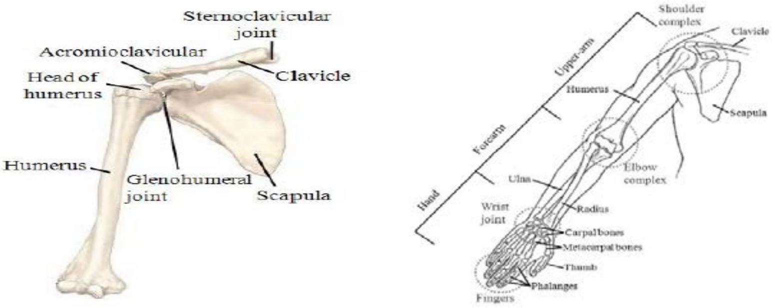
Configuration and structure of Human upper limb

There are many considerations that must be taken in consideration in the design of rehabilitation robot. Ideal robotic rehabilitation devices must be able to:

1) Move with free motion; that means robot trains the complete functional workspace of a human upper limb with three dimensions motion to improve efficiency of therapy robotic devices.
2) Activate joint by joint to induce exact ergonomic movements in a patient. This is important to make the input sequence of the nervous system.
3) Be no discomfort or safety hazards for the user during movement.

To allow the training of a daily livings, the robot must be able to move the patient's arm in all its degrees of freedom and to position the human's hand at any given point in the three dimensional space. In the design of rehabilitation robot, there are many design difficulties to achieve a proper mechanical design of an upper-limb rehabilitation robot. Most of them are represented by the anatomy of the upper-limb. One of the anatomically complex areas in the human body is the shoulder complex. Its center of rotation is changing with its motions. One of the difficulties to be solved is the design of a proper shoulder mechanism for an upper-limb rehabilitation robot that changes its center of rotation with its motions [4].

In order to build the mathematical model for human upper limb, the upper limb biomechanical structure must be understood. The human upper-limb mainly consists of shoulder complex, elbow complex, wrist joint, and fingers have several joints as shown in Figure (1) [3].



Figure(1)Human upper limb biomechanical structure [3].

The main motions of the shoulder complex are provided by the glen humeral joint of shoulder complex; shown in Figure (2).

(a) (b) (c) (d)

Figure (2): Main motions of shoulder complex:
(a) Flexion-extension, (b) Internal-external rotation (c) Shoulder abduction-adduction, (d) Elbow flexion-extension.

The problems of currently known rehabilitation robots are their limitations in workspace, lack of ability to smooth interact with human arm motion, and singularity in robot device that interact with human limb. Alignment problem for each robot design is another problem that should be considered.

Some of rehabilitation robots are wearable and othersare non-wearable. The wearable device requires alignment to the biological joints, while non-wearable device has disadvantages related to redundancies in human arm which prevent actuation in all DOF.

The overall structure of proposed 3DOF rehabilitation robot for human upper limb motion design is shown in Figure (3). This structure is manufacturing with respect to medical designs of rehabilitation robots from bars of steles steel metal and welding by argon welding. This design has adjustable mechanism for robot base. The adjustable length robot links made from aluminum of light weight. Each robot joint is moving using an electric drive, DC servo motor with gearbox that generates appropriate torque for robot motions.

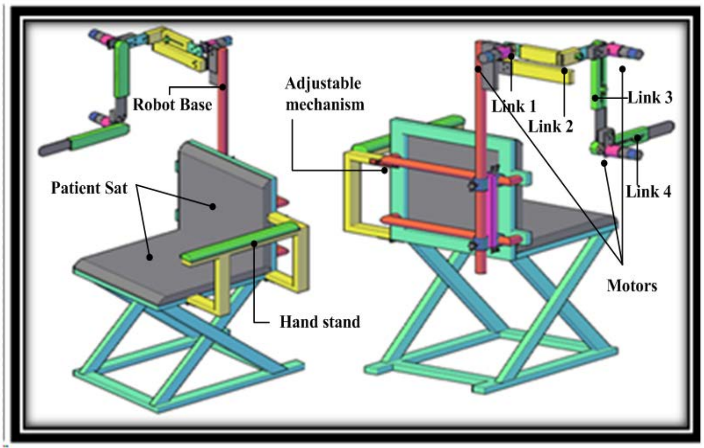


Figure (3)The proposed rehabilitation robot structure with 3 DOF joints for upper limb movements.

Mathematical modeling of the proposed rehabilitation robot

The mathematical model of 3DOF rehabilitation robot is based on the Euler-langrage low in dynamic modeling and depending on Denavit-Hartenberg (DH) method in kinematic modeling.

Kinematical model

In this research, the proposed rehabilitation robot is modeled based on the concepts of, human upper limb articulations and movements to rehabilitate and to ease shoulder and elbow joint motions to assist human daily activity properly. The rehabilitation device has three degrees of freedom, which are:

- Shoulder abduction/adduction (one DOF).
- Shoulder flexion/extension (one DOF).
- Elbow flexion-extension (one DOF).

Joint 1 and 2 are parts from the glen humeral joint, which is known as the shoulder joint, where joint 1 corresponds to the horizontal flexion/extension figure (2-a) and joint 2 corresponds to internal and external rotation but not activate in this proposed design figure (2-b). Joint 3corresponds to the abduction-deduction figure (2-c) andjoint4 corresponds to flexion/extension of elbow joint figure (2-d). Depending on the kinematical analysis of robotics, DH convention [7, 8] is used in this work for obtaining the forward kinematics (end effecter position and orientation). However, Figure (4) shows the schema of 3DOF (active joints) according to DH principles whereθ_1, θ_3 and $\theta_4$are the angles of joints of 1, 3 and 4 respectively andθ_2 is the fixed angle at joint 2 and equals to 90°.

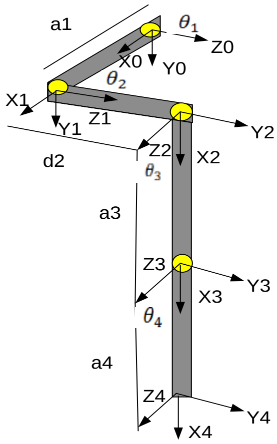


Figure (4) Schema of (3DOF active joints) proposed robot structure.

where a_i isthe distance along X_i from fram e_i(current fream)to the intersection of X_i and Z_{i-1} axes in meter, d_i is the distance along Z_{i-1} from fram e_{i-1} to the intersection of X_i and Z_{i-1} axesin meter, α_i is the angle between Z_{i-1} and Z_i measured about $X_i$in degree. θ_i is the angle between X_{i-1} and X_i measured about Z_{i-1} in degree [7, 8]. The DH parameters according to co-ordinate frames shown in Figure (5) are listed in Table (1).

Table (1) DH parameters.

i	α_i	a_i	d_i	θ_i
1	0	a_1	0	θ_1
2	90°	0	d_2	90°
3	0	a_3	0	θ_3
4	0	a_4	0	θ_4

As result, the homogeneous transformation matrix is [7]:

$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{....(1)}$$

Using (1), the individual homogeneous transfer matrix that relates two successive frames can be written as follows:

$$A_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & a_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & a_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, A_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & d2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & a_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & a_3\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } A_4 = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & a_4\cos\theta_4 \\ \sin\theta_4 & \cos\theta_4 & 0 & a_4\sin\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The homogenous transformation matrix that relates frame (4) to frame (0) can be obtained by multiplying individual transformation matrices:

$$T_4^0 = A_1 A_2 A_3 A_4 \quad ...(2)$$

This transformation matrix represents the positions and orientations of the reference frame attached to the end effecter (axis 4) regards to the fixed reference frame.

Dynamic model

Using the Euler–Lagrangian formulation, the dynamics of robot manipulators with rigid links can be written as [7]:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + F(\dot{q}) + G(q) + \tau_{dis} = \tau \quad ....(3)$$

Where q $\in R^n$ denotes the vector of generalized displacements, $\tau \in R^n$ denotes the vector of generalized control input torques, D(q) $\in R^{n*n}$ is the inertia matrix, $C(q,\dot{q}) \in R^{n*n}$ is the Coriolis matrix, $F(\dot{q}) \in R^n$ are the Friction terms, G (q) $\in R^n$ is the gravity vector, and $\tau_{dis} \in R^n$ represents disturbances which are bounded [7].

In this work, the proposed robot consists of only four links where three of them have active joints while link2 has a fixed angle. Thus, all derivations depend on active angles θ_1, θ_3 and θ_4 only. The elements of D and C matrices are functions of θ_i, M_i, a_i, lc_i and I_i where M_i is the i^{th} link mass (kg), a_i is the i^{th} link length (meter), lc_i denote the i^{th} distance from the previous joint to the center of mass of link i in meter, I_i denotes the moment of inertia of link i about the axis parallel to rotation axis of link i passing through its center of mass ($\mathbf{kg.m^2}$) [7].

The moment of inertia of each link is calculated around the center of mass of link i, at axis passing through link center of mass and parallel to rotational axis of link i,around Z axis:

$$\mathbf{I_{zz} = \frac{M_i}{12}\left(W_i^2 + L_i^2\right)} \quad ....(4)$$

where I_{zz} is moment of inertia of link i around its center of mass, W_i is the width of link i in meterand L_i is the length of link iin meter.

Friction model

Friction is an undesirable phenomenon in the performance of controlled electromechanical motion systems. The effect of friction on robotic system depends on many factors such as lubrication, temperature, interaction surface, displacement and relative velocity of robot. It is highly nonlinear effect and result in steady state errors, limit cycles, and poor performance [9].

To model the robot accurately, the effect of friction in a robot is added in each joint. The friction model that incorporates frictions phenomena (Coulomb plus viscous and stribeck friction) used in this paper is [10]:

$$F(v) = \left[F_C + (F_s - F_c)e^{-\left|\frac{v}{vs}\right|^{\delta}}\right]sgn(v) + \beta v \quad .... (5)$$

This equation incorporate all friction phenomenon's in one model, where v in rad/sec is robot joint velocity, F_C is Colombo friction in N, F_s is stribeck friction in N, β viscous coefficient in N, vs is the Stribeck velocity that defines the region in which such an effect is present, and δ constant that can be equal to 2 (but not necessarily) [10].

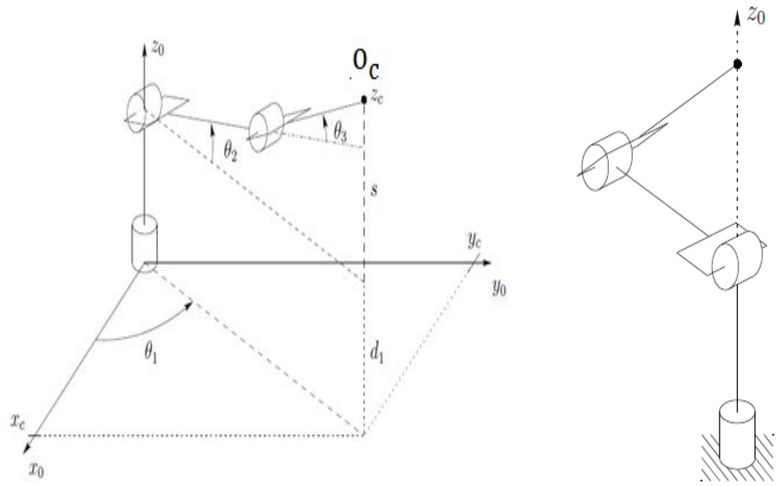
Solving Singularity problem

To cancel out the all effects caused by the position difference between the center of rotation of the robot shoulder and that of the human shoulder, the mechanical singularity should not be occurred within the workspace of the robot. There are several mechanical solutions for singularity as in [3and 11].

In this work, the singularity occurs at configuration of the end effecter with the base of robot. See Figure (5-a),where x_c, y_c, z_c are the coordinates of end effecter are frame at$o_c$and$\theta_1$is calculated by geometric approach as:

$$\theta_1 = \tan^{-1}\frac{y_c}{x_c} \quad \text{....(6)}$$

The solutionof θ_1, is not valid when $x_c = y_c = 0$. In this case,equation (6) is undefined and the manipulator is in a singular configuration, as shown in Figure (5-b). The end effecter (o_c) intersects (z_0); hence any value of θ_1 leaves o_c is undefined.There are thus infinitely many solutions for $\theta_1$when o_c intersectsz_0.



(a) (b)

Figure (5):(a)Articulated configuration 3DOF, (b) Singular configurations [7].

The solution to the singularity problem is guaranteed by adding an offset($d \neq 0$), as shown in Figure (6).Thus wrist center cannot intersect z_0. By depending on how the DH parameters have assigned for proposed robot, we will have (a_1 = d),see Figure (7).

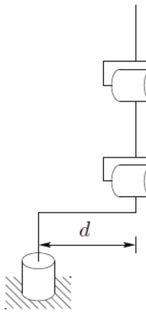


Figure (6)Shoulder offset [7].

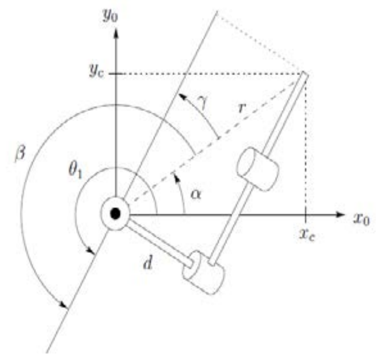


Figure (7)Robot configurations shoulder offset [7].

The mathematical solution for θ_1 with theaddition of an offset is:

$$\theta_1 = \text{atan2}\,(x_c, y_c) + \text{atan2}(-\sqrt{r^2 - d^2}, -d) \qquad \ldots(7)$$

Where:

$$r^2 = x_c^2 + y_c^2$$

The overall dynamic equations that are used to control three drivesfor the robot joints are:

$$\sum_i d_{kj}(q)\ddot{q}_j + \sum_{i,j} c_{ijk}(q)\dot{q}_i\dot{q}_j + \varphi_k(q) + F(\dot{q}) + \tau_{dis} = \tau_k \qquad \ldots(8)$$

Where $c_{ijk}$is known as Christoffel symbols and it's calculated as:

$$c_{ijk} = \frac{1}{2}\left[\frac{\partial d_{kj}}{\partial q_i} + \frac{\partial d_{ki}}{\partial q_j} - \frac{\partial d_{ij}}{\partial q_k}\right] \qquad \ldots(9)$$

where$\tau_k$is the applied torque to each joint,$q_i$is the angular displacement, $\dot{q}_i$is the angular velocity and $\ddot{q}_3$ is the angular acceleration.Matrix, $\varphi(q_i)$ isthe potential energy, $F(\dot{q}_i)$ is the friction equation and $\tau_{dis\,i}$ is the external disturbance that applied to the robot.

Force-Position controller

Force-Position controller is a control strategy specifying a desired dynamic behavior for the robot. The robot controller is designed to track the motion trajectory and realize the desired force dynamics between the end-effecter position and the contact force [12]. The desired force is defined as:

$$F_d - F = K_d(X_d - X) + B_d(\dot{X}_d - \dot{X}) + M_d(\ddot{X}_d - \ddot{X}) \qquad \ldots(10)$$

WhereF $\in R^P$is the vector of contact generalized forces exerted by the manipulator on the environment, P is the task space dimension. K_d, B_d and $M_d \in R^{P*P}$ are the desired stiffness, damping and inertia matrices respectively, X,$\dot{X}$ and $\ddot{X} \in R^P$are the position, velocity and accelerationrespectively of the robot system in the Cartesian space respectively. The control low of the force that is applied to the dynamic model of robot is [12]:

$$U = J(q)^T[K_p\,(X_d - X) + K_v\,(\dot{X}_d - \dot{X}) + F_d\,(Kf + I) - K_f\,F] + G \qquad \ldots\ (11)$$

Figure (8) represents the block diagramof closed loop Force-Position controlled system for rehabilitation robot where U $\in R^n$ is the control low applied to robot model, J (q) $\in R^{p*n}$ is the Jacobean matrix and K_p, K_v and$K_f \in R^{p*p}$ are the position, velocity and force gain matrices, respectively. In this figure, $Xd = [Pd_x \quad Pd_y Pd_z]^T$ are the desired trajectory coordinates in cm, $Fd = [Fd_x \quad Fd_y Fd_z]^T$ are the joint forces applying to robot joints in N, $\Theta_i = [\Theta_1, \Theta_3, \Theta_4]^T$ are the measured angle from each joint in degree, $F = [F_x \quad F_y F_z]^T$ are the generated force vector in N, $Kf = [Kf_x \quad Kf_y Kf_z]^T$ are the force gains and $u = [u_x \quad u_y u_z]^T$ are the outputs of the fuzzy controllers.

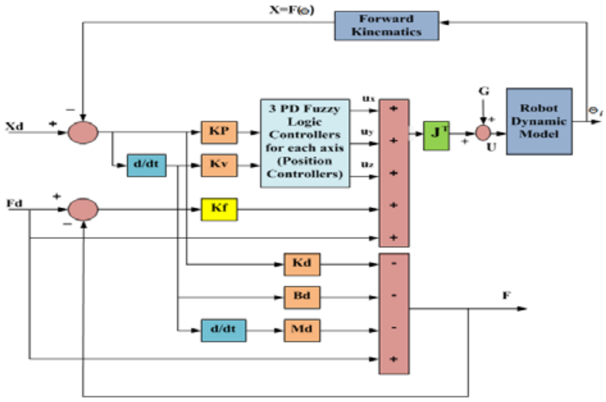
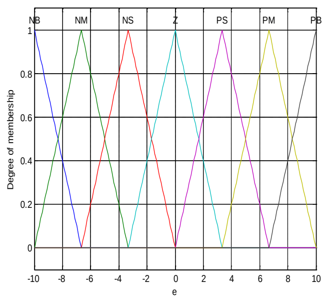


Figure (8) Closed loop Force-position controlled system.

The position controller used in this paper is PD-like Fuzzy Logic Controller (FLC) to deal efficiently with the nonlinearities in robot model. The controller equation is:

$$u(t) = K_p\,(X_d - X) + K_v\,(\dot{X}_d - \dot{X}) \qquad \ldots(12)$$

The inputs to the FLC are e (t) $=X_d - X$is the error signal and$\Delta e(t) = \dot{X}_d - \dot{X}$,is change of error. The FLC is of Mamdani type. The inputs and output membership functions are of triangle shape. This controller hasI/O gains and the defuzzification mechanism is selected to be Centre of gravity method. Figure (9-a) shows the membership functions of the inputs and output and figure (9-b) shows the table of rules of PD-like FLC Position controller.



$\dot{e}$ / 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

(a) **(b)**

Figure (9) (a) I/O Membership functions of FLC (b) Table of rules of FLC.

Where e, $\dot{e}$ are error and change of error respectively as input for FLC. The linguistic variables of FLC areNB(negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), and PB (positive big).

Simulation of the proposed robot

All Simulink models have done by MATLAB (R2010a). The forward kinematic Simulink model is shown in Figure (10).

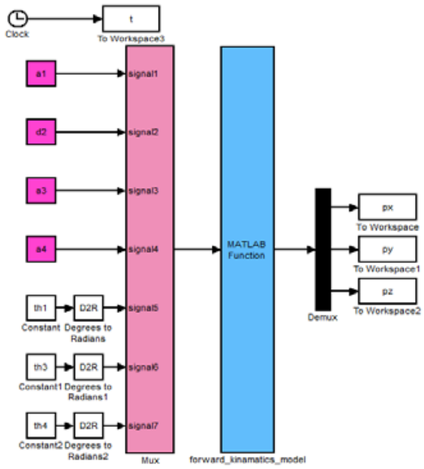


Figure (10) Forward kinematic Simulink schema.

The parameters of the proposed robot model are selected as$a_1 = 0.148$ m, $d_2 = 0.1$ m, $a_3 = 0.341$ m and $a_4 = 0.311$ m [13]. The mass for each link is $m_1 = 0.36$ Kg, $m_2 = 0.4$ Kg, $m_3 = 0.63$ Kg and $m_4 = 0.28$ Kg. Table (2) shows the limits for each joint [5, 6].

Table(2) Limits of proposed robot movements [5, 6].

Types of Motion	Anatomical limits	Robot limits
Shoulder Joints		
Flexion	$170^\circ - 180^\circ$	140°
Extension	$30^\circ - 60^\circ$	0°
Abduction	$170^\circ - 180^\circ$	140°
Adduction	50°	0°
Elbow joint		
Flexion	$140^\circ - 145^\circ$	120°
Extension	$0^\circ - 15^\circ$	0°

Moreover, Friction coefficients model for each joint are taken from [9] where viscous coefficient (B)is 0.0801 (Nms/rad), Coulomb Friction Force (Fc) is 0.3939 (N), Static Friction Force (Fs) is 0.5431 (N) and the Stribeck velocity (vs) is 0.0758 (rad/s). Figure (11) shows the Simulink structure of the friction model,(eq.5). However, the Simulink model of the dynamics for 3DOF rehabilitation robot is shown in Figure (12).

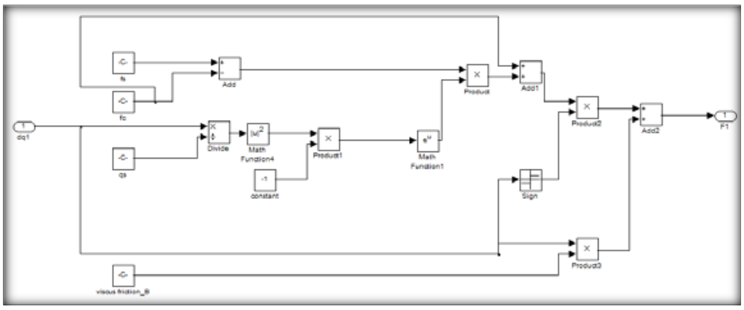


Figure (11) Simulink of Friction model.

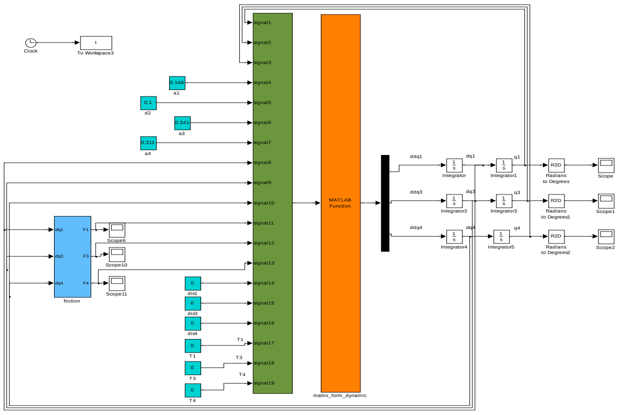


Figure (12) Dynamic model of 3 DOF active joints rehabilitation robot.

By applying zero input torques for all joints to the open loop dynamic model where the friction at each joint is added and also applying 0.12sin(ωt) as a disturbance upon the last joint, this disturbance forms the unexpected shocks to the hand, such as Parkinson's, the responses of the angles of the active joints are shown in Figure (13).

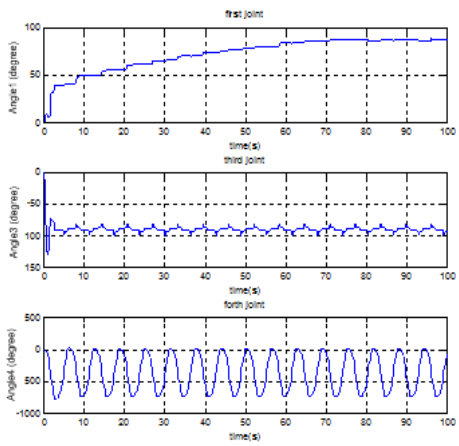


Figure (13) Open loop response with a disturbance applied upon the forth joint.

Moreover, the parameters of the Force controller, equation (10), are selected to as KD=60 (N/m), Bd=150 (N·s/m) and Md=2 (kg) [14].These values were representing a selected stable second order model with damping ratio and un-damped natural frequency of ζ=0.785and *wn*=0.523rad/sec respectively. Table (3) shows the gains of the Force-Position controller. These gains were obtained by tuning the controller by trial and error in order to make the robot end effecter tracking the desired medical trajectories in a specific time with minimum overshoot, minimum settling time and minimum steady state error. The Simulink block that represents the closed loop Force-Position controller of rehabilitation robot is shown in Figure (14).

Table (3)Force-Position Controller's gains.

Controller	**Gains**		
Position controller	**Proportional**	**Derivatives**	**Output gain**
Fuzzy_X	1	0.1	25
Fuzzy_Y	4	0.1	22
Fyzzy_Z	3	0.01	7
Force controller	**Kfx**	**kfy**	**kfz**
	0.01	0.01	0.01

Simulation results of Force-Position controlled robot

The desired reference trajectories are generated by using a cubic interpolation. The initial and final end effecter joint angles of the robot are $\Theta_{3d}(t_0) = 0$, $\Theta_{3d}(t_f) = 90^{\circ}$ for shoulder abduction, where t_0 is the initial time and t_f is the final time of motion. The other joint angels are assumed to be zero. The trajectory is time of planning in such a way that the robot arrives at the final configuration in t_f= 100 s. the planned trajectory is given by [14]:

$$\Theta_{3d}(t) = \Theta_{3d}(t_0) + 3\left[\frac{\Theta_{3d}(t_f)-\Theta_{3d}(t_0)}{t_f^2}\right]t^2 - 2\left[\frac{\Theta_{3d}(t_f)-\Theta_{3d}(t_0)}{t_f^3}\right]t^3 \qquad \ldots(13)$$

$$\Theta_{4d}(t) = \Theta_{4d}(t_0) + 3\left[\frac{\Theta_{4d}(t_f)-\Theta_{4d}(t_0)}{t_f^2}\right]t^2 - 2\left[\frac{\Theta_{4d}(t_f)-\Theta_{4d}(t_0)}{t_f^3}\right]t^3 \qquad \ldots(14)$$

where$\Theta_{id}(t)\{i=3, 4\}$ is the generated angle for desired trajectory. This trajectory is transformed into Cartesian coordinates using the direct kinematics in order to obtain the desired trajectory $x_d = [x_d y_d z_d]^T$:

$$x_d(t) = a_1 \qquad \ldots(15)$$

$$y_d(t) = a_3 \cos(\Theta_{1d}) + a_4 \cos(\Theta_{1d} + \Theta_{2d}) \qquad \ldots(16)$$

$$z_d(t) = -a_3 \sin(\Theta_{1d}) - a_4 \sin(\Theta_{1d} + \Theta_{2d}) + d_2 \qquad \ldots(17)$$

Where:

Θ_{1d} and Θ_{2d} are desired input angles for trajectory in (degree), a_1 , d_2 ,a_3 and a_4 are the length of robot links in meter.

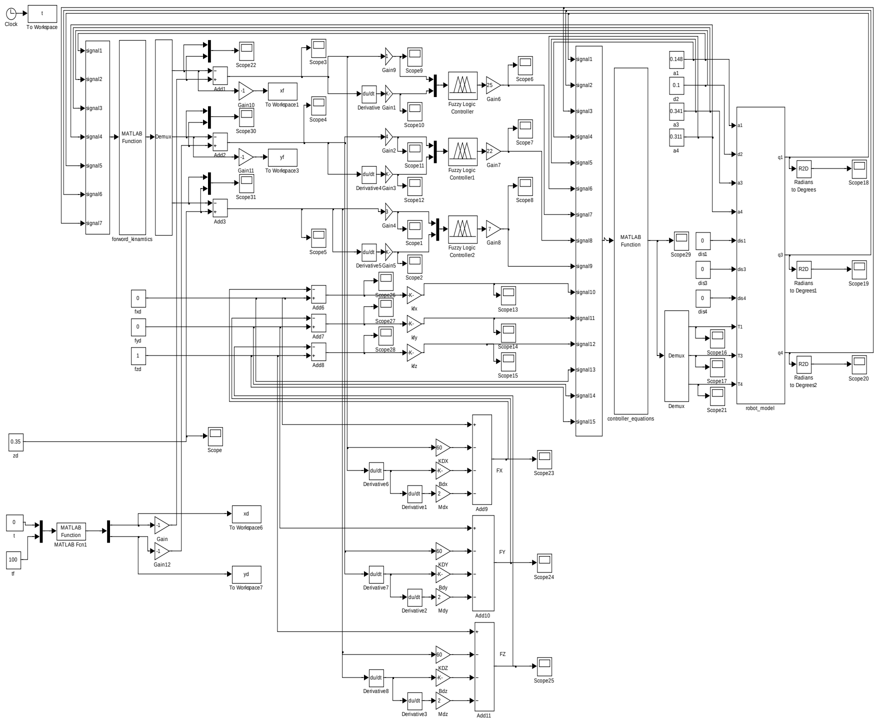


Figure (14) The complete controlled system of rehabilitation robot.

By applying desired force $F_d=[0\ 0\ 1]^T$ in (N), the position responses of the end effecter with out and with the addition of disturbance of (0.12sin(ωt)) are shown in Figure (15).

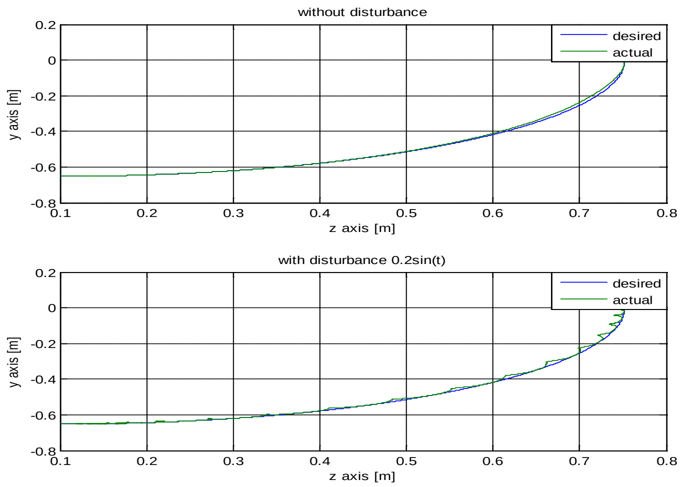
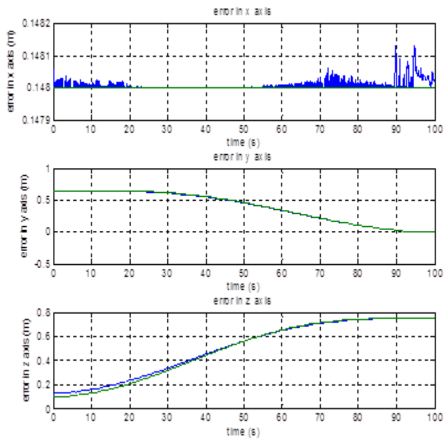


Figure (15) Position response of closed loop controlled system.

The error in position of each link is shown in Figures (16) and (17) respectively.



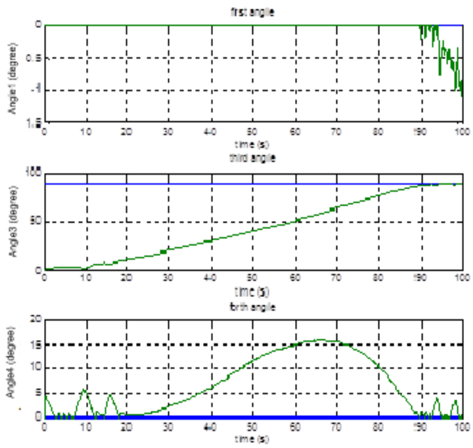


Figure (16) Errors in position without applying disturbances.

Figure (17) Error in joint angles without disturbances.

Applying another reference trajectory of half ellipse that is using to move the three joints together at the same time, Figure (18) shows the response of end effecter position without and with the effect of disturbance in forth joint using the same previous desired forces.

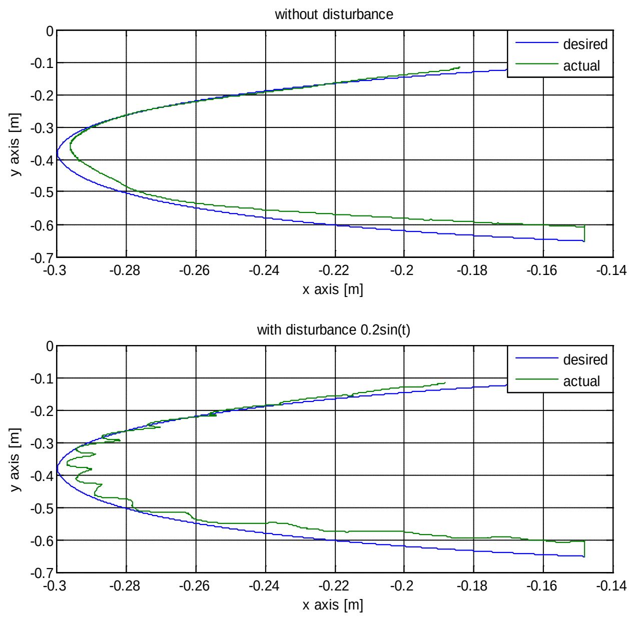
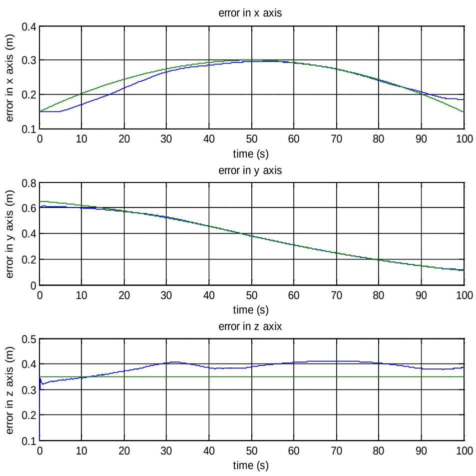


Figure (18)End effecter position responses with ellipse trajectory in x, y plan and fixed dimension.

Moreover, the errors in position for each axis are shown in Figure (19) and the responses of the active joint angles in are shown in Figure (20).



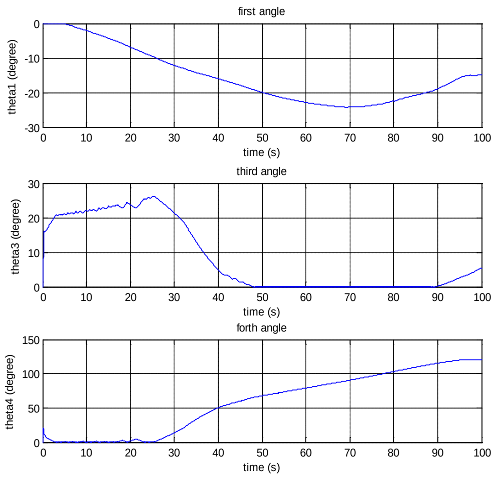


Figure (19) Errors in position for each axis without disturbances

Figure (20) Joint angles responses with disturbances.

CONCLUSIONS

In this work 3DOF rehabilitation robot model was designed and simulated using MATLAB/Simulink. Three Intelligent Force-Position controllers were designed in order to make the robot end effecter tracking the desired medical trajectories in a specific time with minimum overshoot, minimum settling time and minimum steady state error. These trajectories represent the therapy for patient limbs, and by training with time, the injure limb will be hold and do all its functions of daily living. Each controller consists of PD-like Fuzzy logic controller designed for position control and PD controller designed for Force control.

Singularity problem in the proposed structure is solved, since robot the structure includes a shoulder offset (a_1), thus the end effector will not intersect the Z-axis of robot base. Also, the friction phenomenon do not affect in position response because of using an intelligent controller that deals with friction and higher nonlinearities in robot model.

Theoutput position trajectories satisfy the desired oneswith minimum overshoot, minimum settling time and minimum error in end effecter position.The maximum errors exist in each axis without applying disturbance is: 0.0004 (meter) in X axis and 0.003 (meter) in Y axis. By applying disturbances, the maximum error found to be 0.0002 (meter) in X axis and 0.01 (meter) in Y axis. By comparing these results with PD Force-Position controller in [12], it was found that the position of the end effecter is fluctuatedaround the desired trajectory because this type of controller does not compensate the effect of friction and other nonlinearities that exist in the model. In the contrary, this does not exist when using Intelligent Force-Position control.

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