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Design and Control of a Rehabilitation Arm Robot to Regulate the Patient's Activity using the Integrated Force Control and Fuzzy Logic

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Abstract

The main purpose of this paper is proposing the controller system for the mechanical arm of the rehabilitation robot. For this purpose a professional controller is designed for the non-linear system of the robot with 3 degrees of freedom. In the dynamic modeling of the system, the Lagrange method will be used and the system model will be obtained. One of the issues in controller design is an uncertainty which shows itself in the form of noise and disturbances in the system. In the design of the controller, uncertainty should be considered for some sensitive parameters of the system and the final controller should be made more practical, which is robust to uncertainty. In alternative systems and robots that are designed to perform human activities, the main goal is to enhance the behavior of the robot closer to the real arm of a healthy person, both in terms of ability and flexibility. The goal of designing a control system is that it can maintain the normal performance of the system and behave stably in the presence of various system uncertainties such as length, weight and external disturbances applied to the arm. Outer covering refers to an enabling structure that enhances a person's physical capabilities. The main application of the proposed system is such as increasing the power of a sick person or a normal person with more efficiency, to regulate the behavior of the stimulus connected to tactile devices and also physiotherapy.

Keywords: Rehabilitation arm robot, Rehabilitation arm robot, Force control, Fuzzy logic

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1. Introduction

A review of the history of robotics and its progress shows the closer interaction between humans and robots. At first, robots were used in industrial environments as a substitute for humans in performing repetitive and boring tasks and in tasks that required high precision. But today we are witnessing an increasing increase in human-robot interaction. In other words, this interaction is expanding from the mere exchange of information (in remote work tasks, Teleoperation and Telemanipulation) to a close physical and cognitive connection with humans. For this reason, a concept called cover robots has been created. Recent research in the field of robotic rehabilitation has led to exoskeleton robots. Exoskeletons have a structure similar to the joints of the human upper body. Appropriate control methods are necessary to coordinate exoskeleton movements with human organs (Li et al., 2022; Li et al., 2020; Xu et al., 2011). Common methods include position control and impedance control (Liu et al., 2020; Wu et al., 2019; Moshaii et al., 2019; Nef and Riener, 2005). In order to eliminate the effects of friction and gravity forces, friction and gravity compensators are used (Wu et al., 2018). In recent years, advanced methods have been used by researchers to control exoskeletons. For example, in (Feng et al., 2022), proportional-derivative controller is used in passive rehabilitation mode and fuzzy-neural biological controller is used for active rehabilitation mode. In (Chen et al., 2016), the inverse torque control method is used, and in (Wang et al., 2020), the sliding mode control is used. Muscle voltage signals indicate muscle activity and can be measured using electrodes placed on the skin. Various researchers have used these signals to control exoskeletons (Oyman et al., 2020; Feng et al., 2020). Muscle voltage signals can also be used to estimate the dynamics of organs (Meng et al., 2021), this information is very useful in creating a suitable model of the user's body. In this article, by reviewing the previous works, the robust control for the human arm rehabilitation robot is presented so that it can perform the work of the human arm to help the patient by taking into account the uncertainty of the system.

1.2 Control based on human-robot cognitive interaction

In this method, human-robot cognitive interaction signals are used as control inputs and are divided into two categories: control based on user commands and control based on muscle voltage signal. Figure (1) shows the Block diagram of these control methods. The control method based on user commands (Figure (1) (a)) is used in rehabilitation applications to train muscles by performing repetitive movements, and to improve daily activities in power-assisted robots. In this method, the healthy parts of the human body are used to produce the movement commands of the robot to help the problem organs. However, in this method, the function of healthy organs is limited and the production of unnatural movements causes discomfort to the user (Liu et al., 2020). The control based on the muscle voltage signal (Figure (1b)) predicts the user's movements by measuring the microelectrical signals of the human body that are generated during movement. This method is used in auxiliary and power augmentation systems to produce robot movements. In (Li et al., 2017), by measuring the muscle voltage signals and the information related to the joints, using the muscle Hill model, the torque required for the user's movement is predicted. This control method quickly measures the user's movements and estimates the required torque, but since the biomedical signals are different for different people, it makes it difficult to generalize this method. Also, processing these signals is very difficult. In this research, the human model of the robot system is able to interact with humans. Then the design of stiffness controller based on fuzzy logic for the modeled system will be discussed. The goal of this research is to obtain a control law that can achieve the goals of the rehabilitation robot in tracking the path under certain forces, finally the results of the simulation of the rehabilitation robot and the discussion of the results are presented.

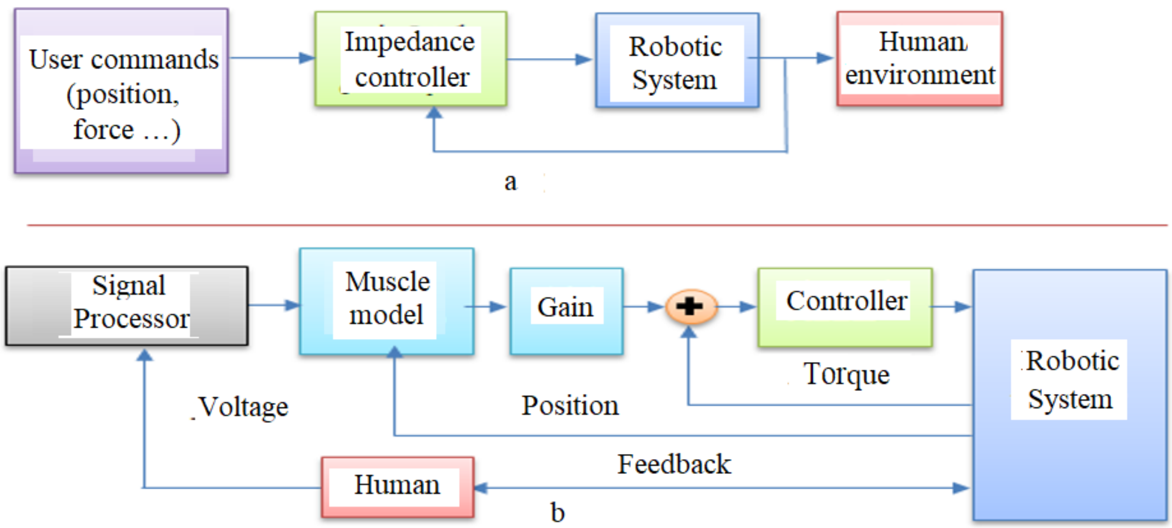

Figure 1: Block diagram of controllers based on human-robot cognitive interaction. (a) control based on user commands, (b) control based on muscle voltage signal.

2. Method

2.1 Dynamic modeling of the arm

The process of dynamic modeling of the arm has various complexities, and in these theses, this model and its effect will be assumed in the form of force and in indefinite rates. The parameters of the arm are listed in tables (1 and 2).

Table 1: Denavit-Hartenberg arm parameters

θ_i	d_i	a_i	α_i	β_i	Joint
0	d_0	a_0	0	0	Basic
β_1+90°	0	0	-90°	$90^\circ\ -90^\circ$	(١)Shoulder
β_2+90°	0	0	$+90^\circ$	$50^\circ\ -180^\circ$	(٢) Shoulder
β_3+90°	0	l_1	0	$80^\circ\ -180^\circ$	(٣) Shoulder
β_4+90°	0	0	$+90^\circ$	$145^\circ\ -10^\circ$	(١) elbow
β_5+90°	l_2	0	$+90^\circ$	$90^\circ\ -90^\circ$	(٢) elbow
β_6+90°	0	0	$+90^\circ$	$70^\circ\ -90^\circ$	(١) Wrist
β_7	0	l_3	0	$40^\circ\ -15^\circ$	(٢) Wrist

Table 2: Anthropometric data of the human body, H indicates the height of a person

Center of mass from the end joint (L%)	The center of mass of the adjacent joint (L%)	Length (L)	Body part
0,564	0,436	0,186H	upper arm
0,57	0,43	0,146H	Forearm
0,494	0,506	0,108H	Hand

2.2 Modeling and controller design

Consider the robotic system with n degrees of freedom described by the following dynamic model in joint space.

$$M(\theta)\ddot{\theta} + H(\theta,\dot{\theta}) + G(\theta) = U - J(\theta)^T F \quad (1)$$

and the following direct kinematic models

$$\begin{aligned} X &= f(\theta) \\ \dot{X} &= J(\theta)\dot{\theta} \end{aligned} \quad (2)$$

where $\theta\,.\,\dot{\theta}.\,\ddot{\theta} \in R^n$ are the position, velocity and acceleration of the joint respectively. $M(\theta) \in R^{n*n}$ is the inertia matrix, $H(\theta.\dot{\theta}) \in R^n$ is the centrifugal vector and Coriolis forces, and $H(\theta.\dot{\theta}) \in R^n$ is the vector of gravity terms. $U \in R^n$ is the generalized joint force vector, $U \in R^n$ is the vector of generalized contact forces applied by the mechanical arm on the leg and P is the dimension of the working space. $J(\theta) \in R^{p*n}$ is the Jacobian matrix and $X.\dot{X} \in R^p$are, respectively, the position and velocity of the robot system connected to the muscle in the Cartesian space. The problem to be solved is the design of the control laws $U \in R^n$ which should satisfy the asymptotic stability of the system described by the dynamic and the kinematic models under the following assumptions: All force, position, velocity and acceleration vectors are measured. All gains used for the control problem are diagonal matrices with equal elements.

2.3 Stiffness control in robot stabilization

In this section, in order to design a control coded method to stabilize the behavior of the covering robot for the disabled person's arm, we use stiffness control. Stiffness control is designed to obtain the reaction behavior of the robot's mechanical arm with the environment in order to make this process as smooth as possible. The block diagram of the complete control system can be described as in Figure 1b. Based on the concept of hardness control, the control law is given as follows.

$$U = J^T\left[K_p\left(X_d - X\right) + K_v\left(\dot{X}_d - \dot{X}\right)\right] + G \quad (3)$$

which $K_p\ \ K_v \in R^{p\times p}$ ،are the velocity and position gain matrix, respectively.

In stiffness control, the joint stiffness matrix is modulated to achieve the desired relationship between position and applied force.

$$F = K_e \left(X_d - X \right) \tag{4}$$

where $K_e \in R^{p*p}$ is the stiffness matrix of the robot/environment system.

2.4 Fuzzy logic in determination of stiffness parameter

In the design of the stiffness rule for the robot system, it is mentioned that considering the force changes and then the error of the output position from the reference value is very important, so that in the rapid changes of the stiffness parameter in the dynamics of the system, it is needed rather than the force controller parameter, which was previously considered as a constant (Figure 2). It could be determined using fuzzy logic and based on Table (3).

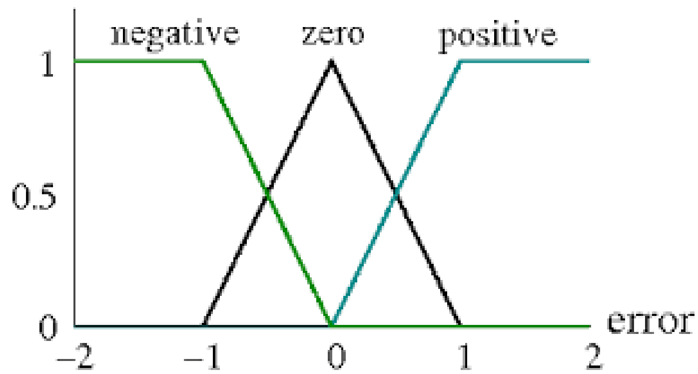

Figure 2: Determine the membership functions for the error input variable

In this model, the fuzzy logic input of the position error is considered and 5 membership functions are used to express it, which starts from a large negative value and goes up to a large positive value. Triangular type has been used in expressing the membership functions because the results of this study have shown that this type of membership function is more effective. On the other hand, by testing the system under different forces, the range of position changes (fuzzy input) has been observed in the area of -0.3 to 0.1, which is considered as the fuzzy input range. On the other hand, the optimal output value of the controller parameter has been measured according to the Lyapunov stability principle of the problem and the optimal value at the maximum output power has been measured and used in the settings related to the fuzzy output range. Based on the desired relationship between the controller parameter changes and the way the output position error changes from the desired value, the following is obtained for fuzzy.

Table 3: Fuzzy logic

Error	NB	NS	Z	PS	PB
Fuzzy gain	T	S	M	B	BB

NB: Big negative; NS: Small negative; Z: Zero; PS: Small Positive; PB: Big Positive; T: Very Small; S: Small; M: Medium; B: Big; BB: Big Big

3. Results

As stated in the modeling and for the design of the control system in the presence of an undetermined external force for the hand rehabilitation robot with 3 degrees of freedom, in Figures (3) to (7) the path tracked by the robot is shown against the reference path. The general shape of the system input in this simulation was considered as a continuous and derivable path, which was considered as the command path for the cover robot, and in this regard, from an external force in order to evaluate the resistance of the system against Used with indefinites. The general shape of the path was considered as a semi-circular path, which is fixed at the end point of the semi-circle at the end of the work. The diagram of this route was considered as follows.

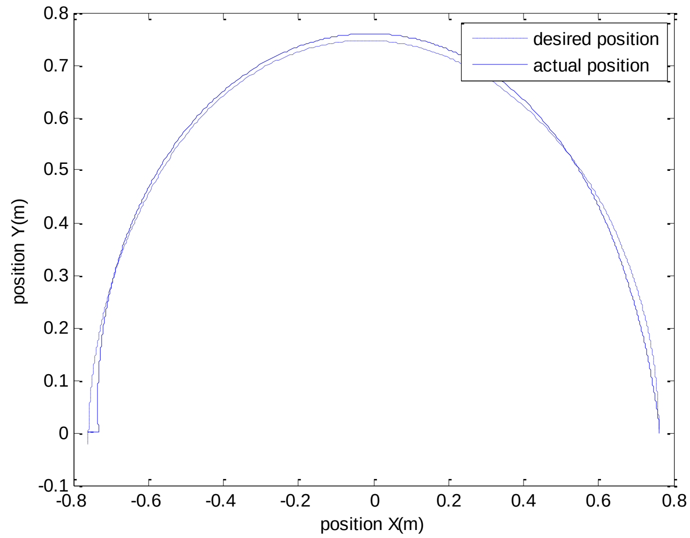

Figure 3: path following

In Figure (3), the semicircular path traveled by the robot with three degrees of freedom in the presence of uncertainty is drawn, corresponding to the desired path. Here a continuous path is determined for the robot to navigate, and the goal is following this path with the least error, which is acceptable in this path be according to the result obtained. In figure (4) and (5) the traveled path is plotted in x and y directions compared to the desired value, it is noted that the robot stays in place after traveling the semi-circular path and the problem is Tracking mode is changed to setting mode.

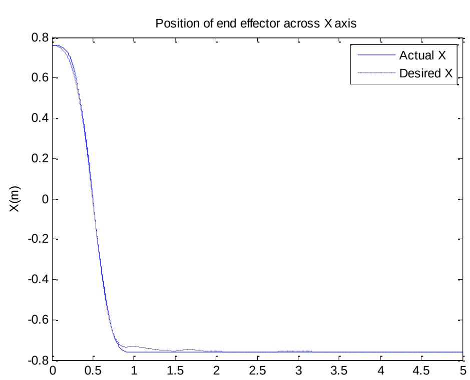

Figure 4: The desired path and tracking by the robot along the X axis

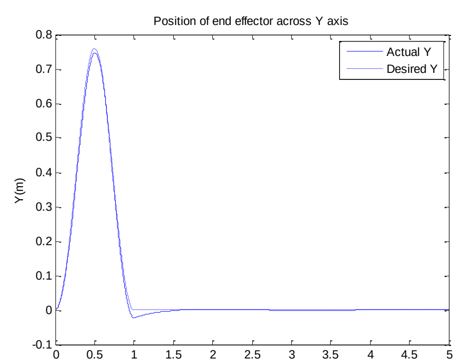

Figure 5: The desired path and tracking by the robot along the Y axis

Figures (6) and (7) show the forces applied by the rehabilitative robot, which is due to the amount of undetermined force with a limit of 10% of the determined force applied from the environment. This force is shown separately in two directions of x and y axis and has transient state values until the undetermined force value is fixed. Considering the uncertain forces in the x and y directions of the robot, it was evaluated, as a result, the final point of the robot or the robot was able to overcome the external forces by applying the appropriate reaction force over the time as follows:

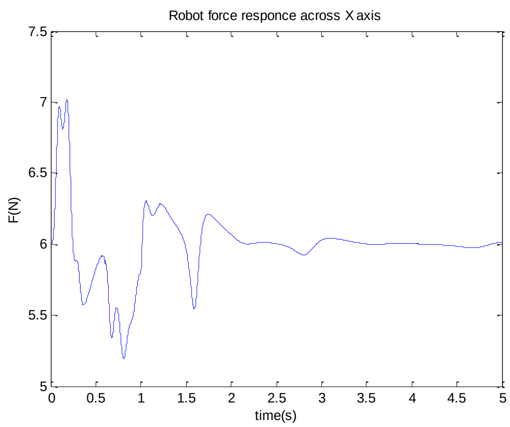

Figure 6: Response of the contact force on the X-axis against the indeterminate force

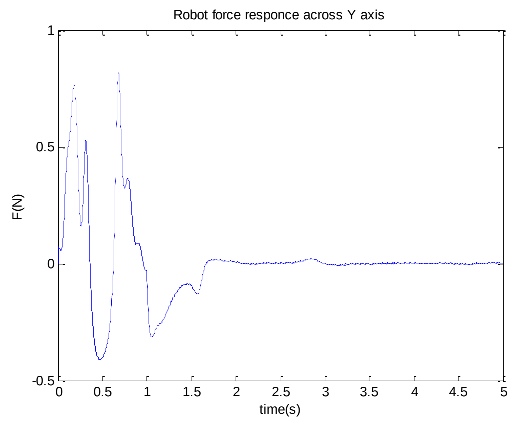

Figure 7: Response of the contact force on the Y-axis against the indeterminate force

Figures (8) to (10) show the control force applied to three joints of the robot, these forces are applied to the first, second and third joints, respectively, and their type is torque type. Considering the uncertain forces in the x and y directions of the robot, it was evaluated, as a result, the final point of the robot or the same robot was able to overcome the external forces by applying the appropriate reaction force over the time as follows:

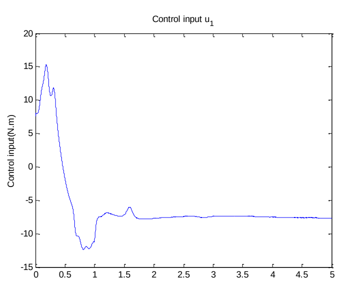

Figure 8: The control law u_1 in the first joint

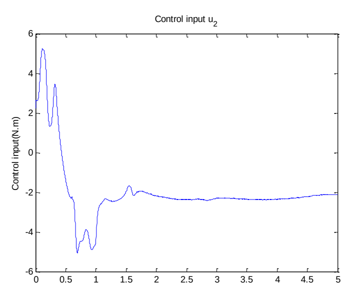

Figure 9: The control law u_2 in the second joint

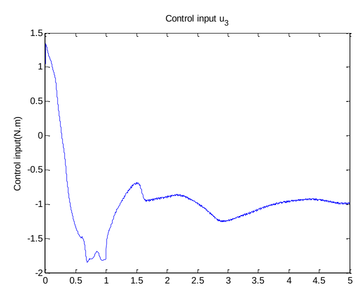

Figure 10: The control law u_3 in the third joint

The rule of these forces was obtained by the operations performed in the third chapter and proved by Lyapunov's rule. On the other hand, the fuzzy logic used in system control was able to change the control gain of the system position according to the system error and improve the control process. This problem showed itself as a reduction in error and control energy consumption.

4. Conclusion

In this research, firstly, after the general review of the rehabilitation robots under the cover robots (exoskeleton) regarding their applications and the general structure and examples of works done in this field, especially in the comparative part, the necessary discussions were conducted and then about the modeling of cover robots for the purpose of rehabilitation. And how the human factor is involved in it was discussed, finally, taking into account the influence of human power and assuming the kinetic, kinematic and stimulus parameters for the robot system, the adaptive-sliding control law was designed. The results obtained from the simulation of the control system have shown the proper performance of the system in controlling the robot, with precision in the working results, the transient time of the system is around 0.1 second and the overshoot rate is less than 5%, also the steady state error for The output variables of the robot in the workspace are around 0. In the design for the three degrees of freedom system of the rehabilitation robot and by using the estimate of the uncertain force on the robot, it is possible to overcome the limited changes in the force on the system and achieve the goal of tracking the position in it. In order to design the control parameters for the system, the control inequalities obtained by Lyapunov should also be considered in it. Obviously, the system in question was able to overcome the uncertain external force that was applied to it in the form of vectors along the x and y axes and produce the appropriate reaction force in this direction, this force can be used to reduce the impact of uncertainty and force an unknown foreigner is effective in the system. In order to improve the controller performance and taking into account the discussion of the control energy spent to control the system, this work can be further considered by optimizing the parameters of the control part of this process. In this work, it is possible to consider a multi-objective cost function including the control force and the amount of error in the outputs, as well as taking into account the limitations of the system, he proceeded to solve the problem.

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