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Adaptive Control of DC motor for one-DOF Rehabilitation Robot

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Abstract: This paper presents an adaptive control technique to control the movement of DC motor for one-DOF rehabilitation robot. Different types of controllers are used to provide accurate positioning of the motor for robots. PID controller is one of the commonly used controllers. However, one limitation of PID controller is that it is not able to adapt the variations in the load, as limb stiffness can be varied from patient to patient and PID is tuned for standard stiffness. Whenever the unknown and inaccessible load torque is imposed, the performance of the robot will be affected and it will have steady state error. Therefore, in this project a model reference adaptive controller (MRAC) is designed for the robot to reduce the positioning error and make the robot beneficial for a wide range of stroke patients. The simulated results show the designed controller is able to cope with the variations in limb's stiffness of the patients without the aid of any additional stiffness detection sensors.

Keywords: Limb stiffness, load torque, Model reference adaptive control, PID control, positioning error.

1. INTRODUCTION

Stroke is one of the leading causes of severe disability. Rehabilitation robots are used to access and improve motor function in the patients after stroke[15]-[17]. The application of rehabilitation robots is increasing rapidly to help in recovering this disability through rehabilitation trainings. They provide automated therapy and enable intense and longer duration repetitive task practice[17], [18]. Moreover, by using a robot, the patient may perform training more frequently. Various rehabilitation robots have been developed with a set of rehabilitation training programs with different haptic modalities[19]. They consist of actuators to produce desired movement of the end effecter that holds the patient's limb for the training. DC motors are the commonly used actuators.

1.1 Rehabilitation Robots

Rehabilitation robots can be classified in different aspects. One classification is according to degree of freedom (DOF). Some robots are developed with only one-DOF to make the robot simple and less expensive so that the patient can easily afford and use it at home without the aid of assistant or therapist[20], [21]. They are usually made for the training of only specific limb. Whereas, some robots have multiple DOF and can be used for the training of different body parts, but they have complex structure and are expensive.

Different types of control techniques had been applied to provide accurate motor control for the rehabilitation robot and PID controller is one of the commonly used controllers because of its simple structure and easy implementation. PI controller was applied by [1] for rotational one-DOF rehabilitation robot for upper limb training. [3], [4] and [5] applied PID controller for the rotary robot, while [2] developed translational movement robot and controlled by PID controller. Impedance control technique was applied by [6] by using load cells as the force sensors for impedance feedback.

For multi-DOF robots, [7] applied Lyapunov direct method with torque sensor to design Neural-Adaptive controller for a 2-DOF robot. [8] designed model-based adaptive controller for RiceWrist robot by comparing the forces required and generated by the patients. One of the commonly used controllers for multi-DOF robots is impedance controller [9]. It requires force feedback from the system to tune the controller parameters.

Since DC motor is generally used as an actuator in one-DOF robots and usually the robots are developed without reducer or gearing to make them back drivable, therefore the main task of control belongs to position control of the motor. Since DC motor has variation in its parameters during operation and also its response is sensitive to load variation, therefore many advance techniques have been applied for the position control of DC motors. [10] and [11] used artificial intelligence techniques for DC motors that results in very complex controller. [12] designed model reference adaptive controller using MIT rule and considered nonlinearities of the motor. It has a simple structure with good response.

Reference [13] did the research on range of mean wrist stiffness of the patients for different kinds of movements.

Table 1 shows the mean wrist stiffness values. In this paper, the controller is designed for one-DOF robot for pronation and supination training of the wrist. From the table, we can find that its range varies from 0.1 to 0.4 Nm/rad.

Table 1. Mean wrist stiffness

Mean Stiffness, Nm/rad			
Movement	Males	Females	Overall
Toward flexion	0.605 ± 0.131	0.429 ±0.192	0.554 ± 0.170
Toward extension	1.146 ± 0.327	0.717 ±0.323	1.021 ± 0.379
Toward radial deviation	1.927 ± 0.521	1.205 ±0.314	1.710 ± 0.573
Toward ulnar deviation	1.328 ± 0.468	1.035 ± 0.315	1.245 ± 0.448
Toward pronation	0.285 ± 0.120	0.135 ±0.107	0.240 ± 0.135
Toward supination	0.217 ± 0.093	0.114 ± 0.083	0.186 ± 0.101

2. PROJECT OVERVIEW

One of the limitations for the PID controller is the low adaptability to external disturbance or load. If the load is over its capability or any variation in the system parameters, as the robot controller is tuned based on a set standard load and parameters. If the robot uses the PID controller, it may not be able to adapt itself to rotate the patient's limb for patient with heavy weight or high muscle stiffness which is common in stroke patient. Thus, it limits the use of the device to only patient with low muscle spasticity. Whenever the unknown and inaccessible load torque is imposed, the system will have the steady-and/or transient-state error. While advanced techniques such as fuzzy logic, artificial neural network, self-Tuning control requires heavy computation for their complex algorithms. Many other techniques such as optimal control, LQR do not take in consideration the change in parameters due to external loading or require sensors for all states of the system.

Therefore, in this project, an adaptive controller which is able to adapt itself based on different patient's condition is proposed to control the position of DC motor for CR2-Haptic, a one-DOF rehabilitation robot that is used to train wrist and forearm movements. The purpose is to reduce the positioning error of the robot and make it more beneficial for a wide range of stroke patients.

2.1 Adaptive control

Adaptive control is a type of controller that has the ability to adjust itself to any parameter variations occurring in a control system. It determines suitable control laws that are satisfactory over a wide range of operating conditions. There are different types of adaptive controller. Some require parameter estimation and some have complex algorithm. Model reference adaptive controller (MRAC) is one of its types and it only requires the reference model of the system.

2.2 Model Reference Adaptive Control (MRAC)

MRAC compares output of reference model and actual plant to produce controller's coefficients. It adjusts itself to parameter variations in a control system and forces the plant response to follow that of the reference model [14]. It can adapt the variation in wrist stiffness without the aid of force feedback. Figure 1 shows the block diagram of model reference adaptive controller for this project.

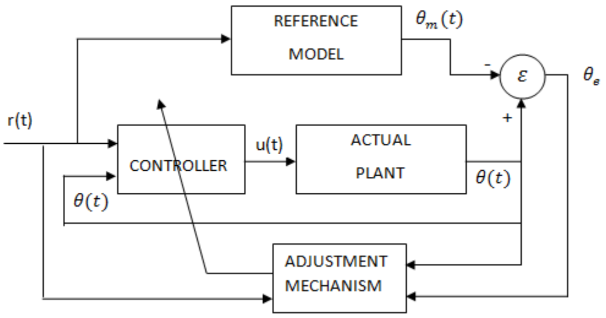

Figure 1. MRAC block diagram of the system

3. METHODOLOGY

3.1 Mathematical Model

The CR2-Haptic used a DC motors without any reducer or gearing to make it back drivable. Therefore we can use the mathematical model of DC motor as reference model in MRAC. Figure 2 shows the schematic diagram of DC motor.

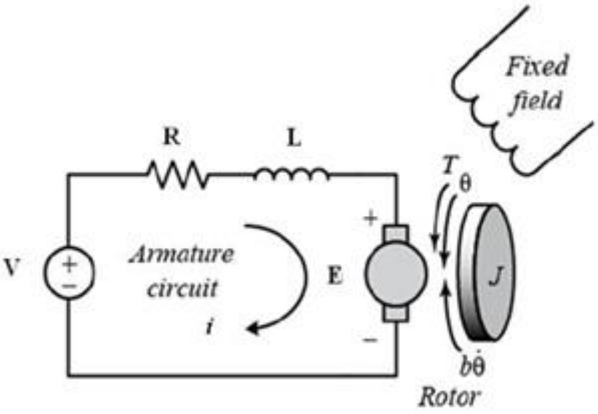

Figure 2. Schematic diagram of DC motor

From schematic diagram, we can get the equation of armature based DC motor using KVL as under.

$$V = Ri + L\frac{di}{dt} + E$$

The motor torque is related to the armature current by the following equation.

$$T = K_t i$$

The back emf E is related to angular velocity by the following equation.

$$E = K_b\dot{\theta}$$

After substitution, the final system model in terms of differential equations will be as follows.

$$\ddot{\theta} + b\dot{\theta} = K_t i$$

$$L\frac{di}{dt} + Ri = V - K_b\dot{\theta}$$

By considering angular position of the motor shaft as the output and applied voltage as input, the transfer function of the system will be a third order and written as follows.

$$\frac{\theta(s)}{V(s)} = \frac{K_t}{s((Js+b)(Ls+R)+K_bK_t)}$$

In DC motors, inductance L of the armature is always very less than its resistance and torque constant Kt almost equal to back emf constant K_b, therefore the system can be reduced to a second order system given as under.

$$\frac{\theta(s)}{V(s)} = \frac{K_t}{s((Js+b)R+K_t^2)}$$

Table 2 shows the values of the required parameters provided by the supplier for the dc motor that has been considered in this project.

Table 2. Given parameters of the DC motor

Parameter	**Symbol**	**Unit**	**Value**
Max Current	Ic	Amps	4.9
Back emf constant	Kb	V/KRPM	7.3
Torque constant	Kt	mNm/Amp	69.9
Resistance	R	Ohms	1.45
Inductance	H	mH	2
Moment of Inertia	J	Kg.cm²	0.325
Viscous friction constant	b	Nms	0.02

Figure 3 shows the simulink diagram of DC motor with PID controller and wrist stiffness is considered as disturbance.

3.2 Controller design

There are two main MRAC design methods Gradient and Lyapunov. Lyapunov method has some advantages over Gradient method that the resulting closed-loop system obtained is always stable. It has fast error convergence and the derived final adjustable parameters are simpler.

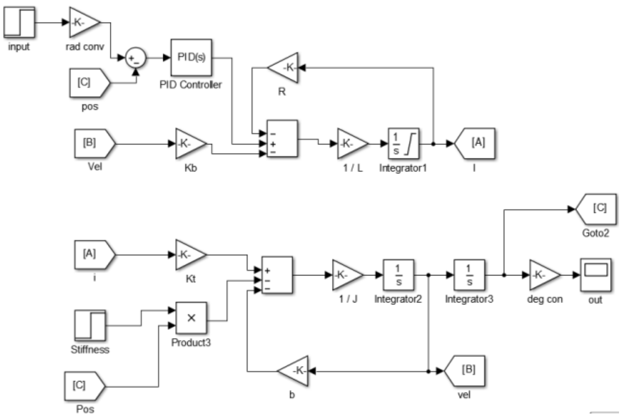

Figure 3. Simulink diagram of DC motor with PID

3.2.1 *Lyapunov Method*

In Lyapunov method, first we derived a differential equation for error that contains the adjustable parameter, α followed by finding Lyapunov function in quadratic form and then derived adaptation mechanism based on Lyapunov function such that e goes to zero.

In this paper, second order transfer function of the DC motor has been considered as the reference model and $u = \theta_1 r - \theta_2 y$ selected as control signal for adaptive mechanism. After derivation by using Lyapunov method, following equations for $\dot{\theta}_1$ and $\dot{\theta}_2$ have been obtained where $\gamma_1 and\ \gamma_2$ are adaptive gains.

$$\dot{\theta}_1 = -re\gamma_1$$

$$\dot{\theta}_2 = ye\gamma_2$$

The Simulink block diagram of the system with wrist stiffness as external disturbance is shown in figure 4, while figure 5 shows Simulink diagram of adaptive mechanism.

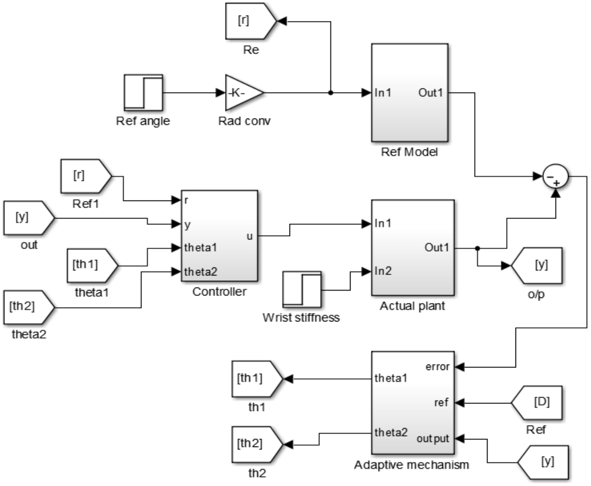

Figure 4. Simulink diagram of the MRAC

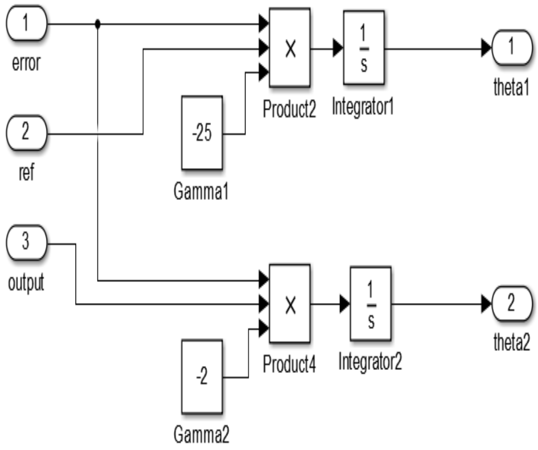

Figure 5. Simulink diagram of Adaptive mechanism

4. RESULTS AND DISCUSSION

The parameters of a DC motor that are provided by supplier have been used in simulation. The set point is a step input of 30 degree that has been triggered after 1 second. Figure 6 shows the response of the DC motor for different values of wrist stiffness using PID controller with preset parameters Kp =1.2, Ki=0.5 and Kd=0.05 that have been calculated without considering the wrist stiffness. From the figure 6 it can be inferred that the controller performed good without considering stiffness while it could not respond satisfactory with the variation in wrist stiffness.

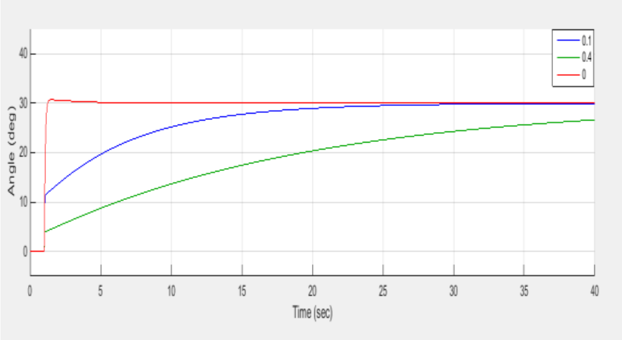

Figure 6. Response of PID controller with small parameter values

Figure 7 is the response of PID controller that is tuned for medium wrist stiffness. The preset parameters are Kp=32, Ki= 80, Kd= 0.17. Although the response does not have position error but it has very fast oscillations that might be dangerous for stroke patients.

By using MRAC with $\gamma_1 = 25$ & $\gamma_2 = -2$, it can be seen from figure 8 that the response is able to reach the desired angle with good transient behavior even with the entire range of wrist stiffness.

Table 3 is the comparison of the PID controller response with Kp=1.2, Ki=0.5 and Kd=0.05 and the designed MRAC response. It can be seen that the designed MRAC has better response time and no steady state error.

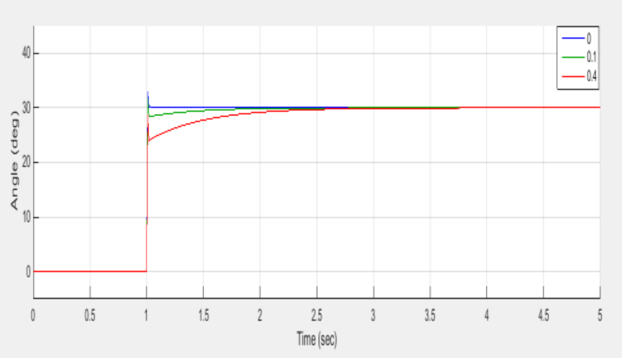

Figure 7. Response of PID controller with large parameters value

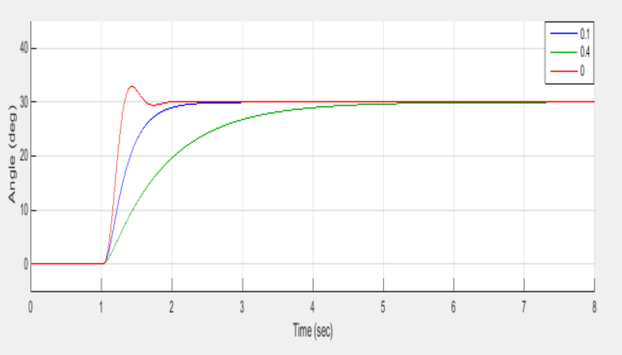

Figure 8. Response of the designed MRAC

Table 3. Comparison of PID and MRAC

	Without wrist stiffness	
Response	Normal PID	Adaptive(sec)
Rise time	0.13	0.27
Settling time	1.08	0.77
Steady state error	No	No
	Wrist stiffness 0.1 Nm/rad	
Rise time	12.03	1
Settling time	22.47	1.91
Steady state error	< 0.05	No
	Wrist stiffness 0.4 Nm/rad	
Rise time	41.11	3.14
Settling time	71.55	5.8
Steady state error	< 0.15	No

5. CONCLUSION

The simulated results show that the designed adaptive algorithm provides good response with up to 12 time reduced settling time and without any steady state error for the entire range of limb stiffness value. Therefore, we can conclude that the MRAC controller will perform better for a one-DOF rehabilitation robot with good position accuracy than PID controller for a number of subjects with varying wrist stiffness. The response can be further improved to acquire the desired transient and steady state behavior, as suggested by therapists, by tuning the adaptive parameters and selecting different control signal.

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