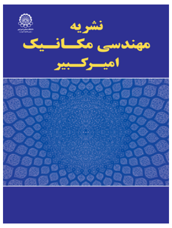

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Design, Modeling, and Optimal Position Control of a New Wrist Rehabilitation Robot Using the Stewart Platform

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ABSTRACT: In this paper, a new application of the Stewart platform is developed for rehabilitation utilities. Stewart robot has a good workspace and load capacity similar to other parallel robots. Here the Stewart model is modified in order to be employed as a wrist rehabilitation robot. Both the direct and inverse kinematics of the robot is extracted using the Jacobian matrix. Afterward, the related dynamic model of the proposed robot is developed using the virtual work method. In order to keep the wrist of the patient within the desired path of rehabilitation, a nonlinear position control is designed and implemented using Computed Torque Method. In order to move the patient's wrist along a safe path, an optimal path is extracted through which, the least amount of acceleration and consequently interaction force will be implemented on the patient's wrist and this path is controlled using Computed Torque Method. With the aid of conducting some analytic simulations in MATLAB the applicability of the proposed robot for wrist rehabilitation is demonstrated. The verification of the model is performed by comparing the results with previous articles while the efficiency of the implemented controller is proved by comparing the actual path with the desired one in presence of disturbance. It is shown that with the aid of the proposed robot and controller, the wrist rehabilitation process of a patient can be successfully accomplished.

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1- Introduction

A rehabilitation robot is a robot used by a patient which can help the person for improving their special limb movements, and maneuvers, as well as increase the strength and resistance of the muscles. There are classic rehabilitation robots that have been developed in the past years with extensive clinical testing. Among them, we can mention the basic designs: MIT-MANUS [1] and ARM [2]. Next, the Bi-Manu-Track robot was made in Germany and had only two degrees of freedom (DOFs) [3]. Martinez et al. [4] used a three-DOFs robot to rehabilitate stroke patients. All the mentioned robots, despite the significant improvements, do not have any forced interaction with the patient's hand.

In this research, an application for the Stewart robot (wrist rehabilitation robot) is introduced. In the upcoming article, firstly, the modeling of the robot is presented. After that, a controller for the mentioned robot is designed using the calculated torque method. Next, in order to implement a safe rehabilitation for patients' wrists, an optimal path for changing the angle of the wrist has been extracted, in which the minimum acceleration and impact are applied to the wrist, and lead to the rehabilitation of the wrist with the minimum possible damage. Then, in the simulation section, the results are presented.

2- Modeling the Proposed Robot

The proposed robot for wrist rehabilitation is a horizontal Stewart platform as follows:

The kinetic of this robot can be represented as the following dynamic model:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=H(q)F \qquad (1)$$

where q is the generalized coordinate vector, M is the inertia matrix, C is the Coriolis matrix, G is the gravity vector, F is the force vector of the actuators and H is the Jacobian matrix of the robot. Now it is possible to locate the hand of the patient like the following figure and move it according to the above-mentioned formulas:

3- Control and Path Planning

In order to achieve the optimal path from the point of view of acceleration and jerk by which the least amount of impulse would be implemented on the damaged wrist of the patient it is required to employ a polynomial with optimum gains. Here a polynomial of order 5 is required to satisfy the initial conditions:

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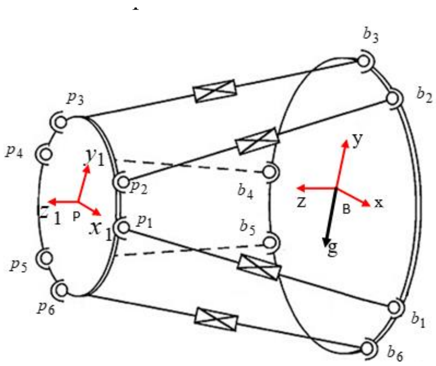

Fig. 1. Stewart robot schematic used in modeling

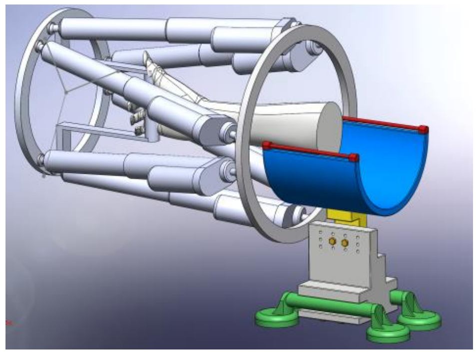

Fig. 2. The schematic of the rehabilitation robot

$$x = x_0 + \dot{x}_0 t + \frac{\ddot{x}_0}{2} t^2 + \frac{20(x_f - x_0) - 4(2\dot{x}_f + 3\dot{x}_0)t_f + 3(\ddot{x}_f - \ddot{x}_0)t_f^2}{2t_f^3} t^3 + \frac{-30(x_f - x_0) + 2(7\dot{x}_f + 8\dot{x}_0)t_f - (2\ddot{x}_f - 3\ddot{x}_0)t_f^2}{2t_f^4} t^4 + \frac{12(x_f - x_0) - 6(\dot{x}_f + \dot{x}_0)t_f + (\ddot{x}_f - \ddot{x}_0)t_f^2}{2t_f^5} t^5 \tag{2}$$

Employing the gradient method, the optimum values of the gains can be extracted as follow:

$$\theta(t) = -\frac{\pi}{4} + 0.08386658583t^3 - 0.02058427240t^4 + 0.001758106753t^5 - 0.00005061757867t^6 \tag{3}$$

In order to keep the wrist within the above-extracted path in the presence of patient disturbances, Computed Torque Method is employed by which the required jacks' force should be implemented according to the following rule:

$$U_{CTM} = M(\ddot{q}_d + U_{PD}) + C\dot{q}_a + G$$
$$U_{PD} = K_P e + K_D \dot{e}, \quad e = q_d - \ddot{q}_a \tag{4}$$

where the subscripts a and d represent the desired and actual components, respectively, U_{CTM} is the applied input load, and K_p and K_d are controller coefficients. The schematic view of the proposed controller for the robot can be shown as the following flowchart:

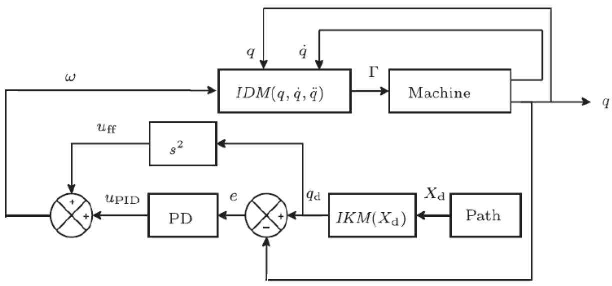

Fig. 3. CTM controller schematic in joint workspace [5]

4- Results and Discussion

In order to check the optimality of the chosen path for wrist rehabilitation, the results of the extracted optimal path are compared with the results of a desired path. The forces required by the actuators to produce these two paths are as follows:

It can be seen that the selected optimal path requires 33% less force for its jacks, which in addition to creating a safer movement for the patient's wrist, also leads to energy savings. Next, for the interaction force between the patient's wrist and the robot during the movement, we have:

As can be seen from Fig. 4, the use of the proposed rehabilitation robot for the movement of the optimal path extracted with the Computed Torque Method (CTM) controller applies about 47% less force impact to the patient's hand.

5- Conclusions

Stewart robot is employed in this article as a novel rehabilitation robot for the wrist. To investigate the correctness of modeling, its related results are compared with previous studies and it was seen that the maximum error is about 5%. A CTM controller was designed and implemented on the system through which any desired path proposed by physicians can be tracked. It was seen that, in the presence of disturbance, the error of wrist tracking can be reduced from 10% to 1% during 2 seconds with the aid of the proposed CTM controller. Also considering the fact that for efficient rehabilitation, the trajectory of the wrist movement is significant, an optimal path was extracted for which the acceleration and consequently its related impulse is minimum during the wrist movement. It was shown that the extracted optimal path reduces the maximum acceleration by up to 48% and its related forces by up to 47% which is extremely useful for patient treatment. Thus it can be concluded that the

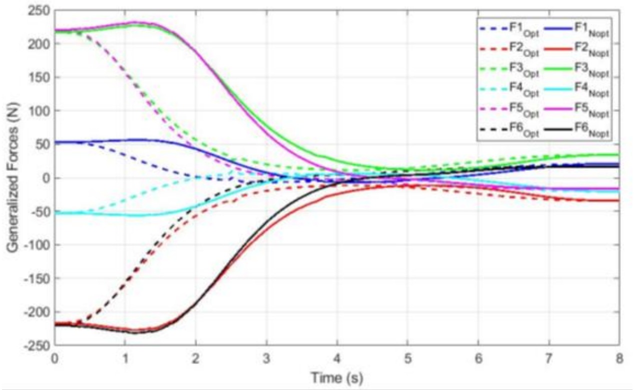

Fig. 4. Comparison between jacks power for these two paths

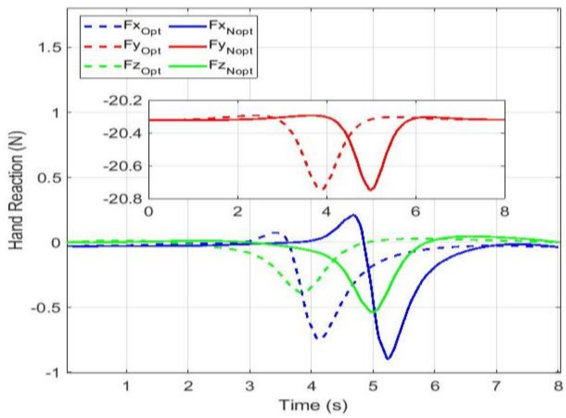

Fig. 5. Comparison of interactive force between the patient's wrist and the robot

proposed robot with the aid of the designed optimal controller can result in proper rehabilitation for the wrist of human during his physiotherapy period.

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