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RESEARCH ARTICLE

Tele-Operated Rehabilitation Robot for Forearm Pronation and Supination in Home Based Therapy

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ABSTRACT - Patients suffering from neurological injuries undergo clinical rehabilitation to regain functionality of the affected limb. However, frequent visits to the therapist tend to be tedious and time consuming. Tele-operated rehabilitation has the advantage of being accessible to patients from the comfort of their homes. This paper presents a tele-operated master-slave rehabilitation robot for forearm pronation and supination for home-based rehabilitation. The prototype of the robot has been developed to provide the rotational motion at the forearm. Arduino is used as the microcontroller board and DC (direct current) motor is utilized to actuate the system. Potentiometers are incorporated at both sides of the robot to provide angular displacement readings. The position of the master sensor is fed to the slave side and this value is then compared to the current displacement of the slave robot and their difference is adjusted. The communication between the master and slave is carried out using Arduino Ethernet shield over the internet. The mathematical model of the robot has been approximated by the dynamic equation of a flywheel. A Proportional Integral Derivative (PID) controller has been implemented on the system to improve its performance. Hardware experimental tests has been conducted and the results verify that the slave robot has successfully followed the master robot's trajectory as required in the design objective with a time delay of 0.1 s. The resulting percentage overshoot is obtained as 17% and the steady state error is 4%.

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1.0 INTRODUCTION

With the increase in the world population and the overall life expectancy, the number of elderlies is drastically rising all over the world. Consequently, the number of patients in need of rehabilitation therapy to recover from disabilities due to aging process is growing each day. There are also patients who are suffering from chronic illnesses, accidents and sports injuries that need to undergo clinical rehabilitations to regain the functionality of the affected limb. However, the frequent and continuous visits to the therapist tend to be tedious and time consuming for both the caregiver and patients, especially for those with low mobility. The number of patients that require the repetitive treatment is also high, causing them to wait in long queues and leads to a lower number of rehabilitation treatments that can be done for each patient. As a result, they are subjected to a slower recovery process and some of them may skip the therapy sessions, which can lead to a more severe medical complications or inability to recover from their impairments permanently.

The application of tele-operated rehabilitation robot for home-based therapy may alleviate these problems. Tele-operation signifies the manipulation of a device from a distance by an operator and has been put into practice successfully in various fields such as tele-manufacturing, tele-maintenance and tele-surgery. Tele-operation systems are essential as they overcome the problems that are arising from a distance and can be used in environments that are unfavorable for humans. In a tele-operated rehabilitation system, the therapist drives the patient's limb motion from the hospitals while the patients stay at the comfort of their homes. This is done by means of master and slave robots. By this way, the patients may avoid all the hassle of travelling to the hospitals for numerous times whilst getting the proper treatments to recuperate.

To date, researches have been conducted on rehabilitation robots [1], [2], [3] and specifically, tele-operated rehabilitation [4 -10] robots to assist the therapists in enhancing the patients' treatment. Buongiorno et al. [4] performed bilateral tele-operation on two isomorphic multiple degree of freedom (DOF) exoskeleton type robots using the master-slave configuration. The master is an impedance-type exoskeleton with good payload characteristics, whereas the slave is a stiff robot involving high level of interaction forces. The resulting bilateral tele-operation system had a communication lag of only 80 ms. Sandoval et al. [5] performed a tele-operation based Doppler sonography by combining an inertial measurement unit with the commercial 3 DOF Novint Falcon haptic device. The resulting 6 DOF device showed promising results with regards to the use of tele-operation for medical procedures. Buongiorno et al. [8] used two exoskeletons, the WRES for wrist rehabilitation and the ALEx (Arm Light Exoskeleton) robot for the therapy of neurological patients by combining their operations using tele-robotics. A one degree of freedom (DOF) lightweight

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exoskeleton with automatic muscle spasticity assessment utilizing the finger tension feedback algorithm has been built by Lai et al. [7] to solve for bulky tele-rehabilitation equipment. Using Industrial Internet of Things (IIoT) platform, Khan et al. [6] developed tele-rehabilitation robots that can communicate bidirectionally through Augmented Reality (AR). The physical motions of the robot can be visualized in other locations using digital twin (DT) structure. The tele-rehabilitation system by Le at al. [10] involves the utilization of a virtual reality (VR) environment and the quality of the interaction between the user and the system is enhanced by the implementation of nonlinear autoregressive models with exogenous input (NARX) and long-short term memory (LSTM) neural networks. In the work by Yang et al. [9], the tele-rehabilitation can be done with the aid of force and visual input. The slave subsystem is incorporated with a variable stiffness robot and the master side is equipped with a haptic device with visual and force feedback. Several tele-operated rehabilitation systems have been developed by various researchers over the years. However, most of them are complicated and involve high development cost.

2.0 SYSTEM DESIGN

The developed tele-operated rehabilitation is shown as in Figure 1. It has been designed to provide forearm pronation/supination movement. The wrist rest as shown in Figure 2 holds the patient's wrist, while the arm rest supports the patient's forearm resting on the other end. The wrist rest is designed with a slot for the Velcro straps so that the patient's wrist can be fasten to the machine. The dimensions of the parts are selected by taking into account the average human body size. Bearings are incorporated to reduce friction between the moving surfaces for a smoother movement. It also decreases the amount torque that the motor needs to supply, which allows for a smaller size motor to be used. This leads to a low robot weight and a compact design.

The same electrical hardware configuration is incorporated in both patient's and therapist's sides. Referring to the system block diagram in Figure 3, Arduino is used as the microcontroller board for the system. The motor shields are stacked on top of ethernet shields on the Arduino microcontroller board. The motor and potentiometer are connected to the rotary link through a gear. Both the master and slave have the same potentiometer placement. The potentiometer in the master side is connected to the Arduino and it serves as the position sensor to send the displacement data to the slave robot. Power is supplied to the motors via an external power supply. Force sensors are placed at both side of the wrist rests. Pressure is applied on the force sensors when the patient's wrist is twisted to the right and left, and the sensor detects the amount of force exerted by the patient. Initially, when the wrist rest are clasped, the reading from the force sensors are higher than zero even though there is no opposing action from the patient. The force reading from each sensor increases depending on the position of the link. At 90°, the force reading from both sensors are ideally equal. When the angle is less than 90°, the force sensor on the right side measures a higher resistance value, while the reading from the sensor on the left side drops and vice versa. The reading from the sensors reach their highest values at 0° or 180°. The force measurement also depends on the weight of the patient's arm, which means that the force reading varies for different users. Therefore, a pre-set threshold value is introduced once the patient wears the tele-operated rehabilitation robot to avoid it from treating these forces as opposing force.

The slave robot is connected to the potentiometer by spur gears. These gears drive the rotary link and wrist rest. The potentiometer feeds the position information to the slave's Proportional Integral Derivative (PID) controller, which compares the position received from master with the current position of the slave robot and then compensates its position error. The counteraction of the patient is sensed by the force sensors attached on the wrist rest and this information is sent to the master robot.

Even though the robot is wearable and mobile, wire connections are used in each local site to reduce the time delay and complexity of the overall system. The communication between the master and slave robots is done wirelessly and established using Arduino Ethernet Shield that is stacked onto the Arduino Microcontroller board, which is connected to the laptop via USB cable. The connection between the Ethernet Shield and laptop is done using ethernet cable (Cat5 or Cat6). The microcontroller reads the position value from the potentiometer at the master side and drives the DC motor over a DC motor driver circuit at the slave side.

In the operational sequence of the tele-operated rehabilitation robot, first, both the master and slave robots determine the threshold values for the therapist's and patient's forces respectively from the values measured by the force sensors. Then, the slave robot checks the position of the master robot continuously and follows the master robot's motion by rotating the slave's wrist rest clockwise or counter clockwise. This is executed in such a manner that compensates the angle difference between the two robots. Next, the master robot checks the force value that is sent from the slave robot continuously. The position and force checking, and the movement of the robots continue in a cycle until the stop button is pressed in either of them.

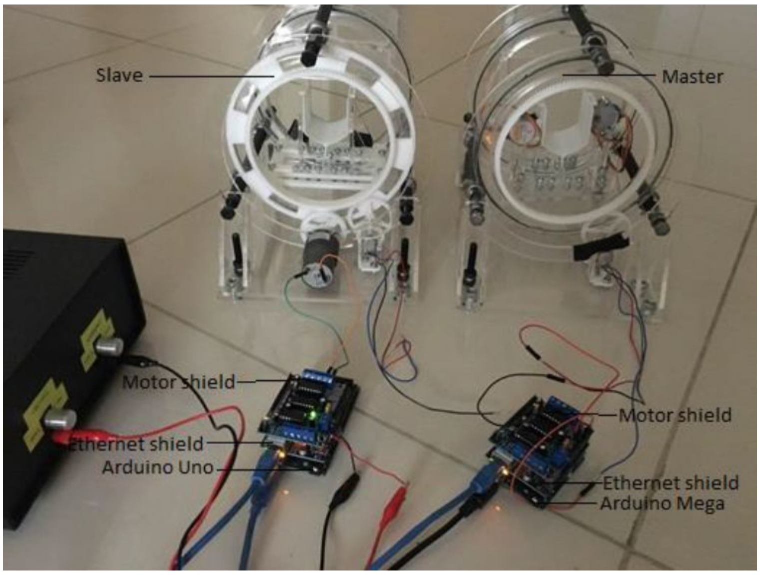

Figure 1. Developed teleoperated exoskeleton for forearm pronation/supination

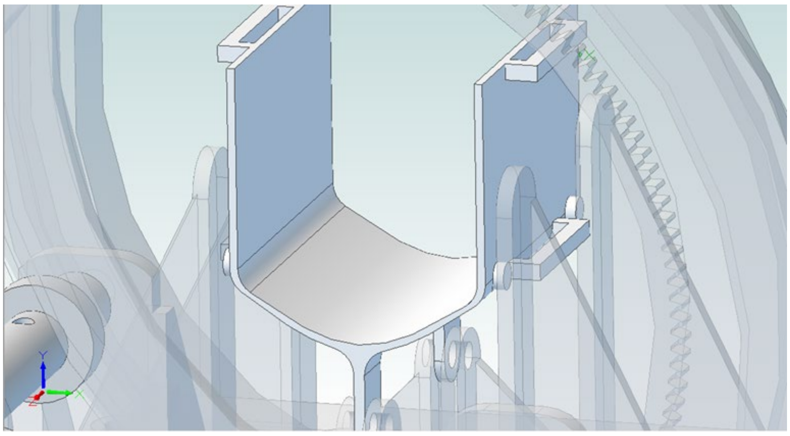

Figure 2. Wrist rest

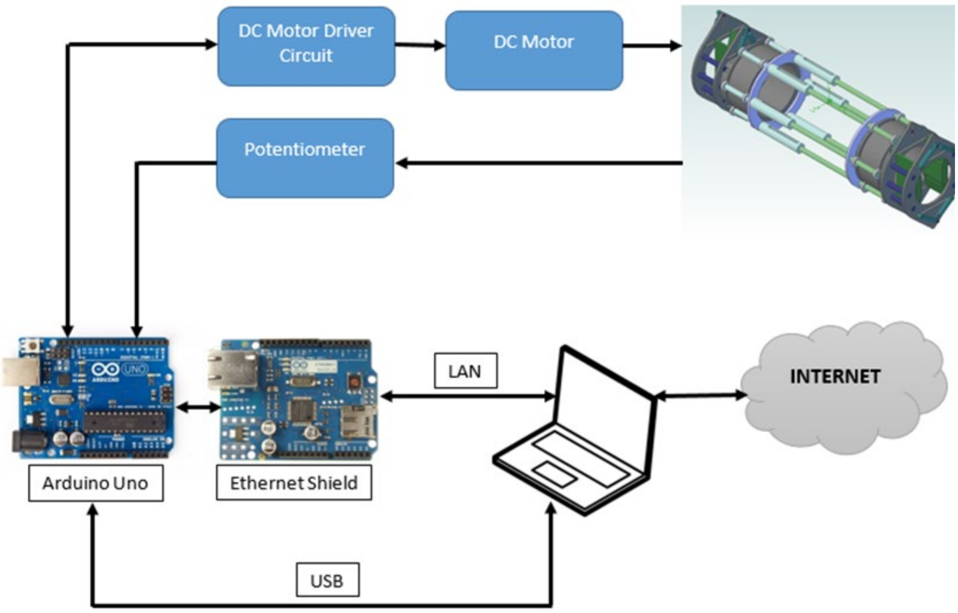

Figure 3. System block diagram on the slave side

3.0 MATHEMATICAL MODELLING OF THE REHABILITATION ROBOT

Each side of the developed tele-operated rehabilitation robot has one degree of freedom (1 DOF) with rotational motion and its dynamic equation is approximated as the mathematical equation of a flywheel. The same mathematical equation applies to both the master and slave parts of the rehabilitation robot.

Applying D'Alembert's law to the free body diagram of the as shown in Figure 4, the mathematical model of the mechanical load can be written as :

$$J_L\ddot{\theta}_L + B_L\dot{\theta}_L + K_L\theta_L = T_L \tag{1}$$

Where J_L, B_L and K_L are the polar moment of inertia, damping ratio and spring stiffness of the rotary part of the rehabilitation robot respectively. T_L is the load torque and $\theta_L, \dot{\theta}_L$ and $\ddot{\theta}_L$ are the angular displacement, velocity and acceleration of the rotary link of the robot respectively.

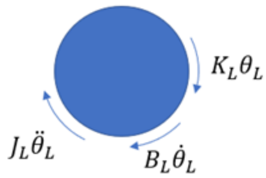

Figure 4. Free body diagram of the rotary part of slave robot

The mathematical model of the mechanical part of a motor can be described by:

$$J_M\ \ddot{\theta}_M + \ B_M\ \dot{\theta}_M + T_L = \mathrm{k_t\,i} \tag{2}$$

Where J_M, B_M , k_t and i are the polar moment of inertia, damping ratio, torque constant and current of the motor respectively. θ_M, θ_M and θ_M are the angular displacement, velocity and acceleration of the motor rotor respectively.

The electrical part of the motor can be represented by the dynamic equation:

$$L\frac{di}{dt}+Ri+k_v\ \dot{\theta}_M=v \tag{3}$$

Where L is the inductance of the armature coil, R is the resistance, v is the supplied voltage and k_v is the velocity constant determined by the flux density of the permanent magnets, reluctance of the iron core of the armature and number of turns in the armature winding. Equations (1) – (3) are used in the simulation test of the system in MATLAB programming environment.

4.0 PID CONTROLLER

Proportional Integral Derivative (PID) controller is applied to the slave side of the tele-operated rehabilitation robot so that its angular position tracks the rotational displacement of the master robot. In this PID control system, the controlled variable is the angular position of the slave robot, the manipulated variable is the voltage supplied, the input or the desired output is the rotational position of the slave robot following the master robot. The PID control law is governed by:

$$v_s=K_p\,e(t)+K_i\int_0^t e(\tau)d\tau+K_d\frac{de(t)}{dt} \tag{4}$$

Where K_p , K_i and K_d are the proportional, integral and derivative control parameters respectively, $e(t)$ is the difference between the position of the master and slave robots, and v_s is the voltage, v in Equation (3) that is supplied to the slave robot's motor. The value of K_p reduces the difference between the actual and desired values, K_i is associated with zero steady state error and K_d improves transient response of the system.

5.0 RESULTS AND DISCUSSIONS

5.1 Simulation Test

The PID controller in Equation (4) has been implemented on the slave side of the tele-operated rehabilitation robot for the forearm pronation/ supination motion, which is represented by Equations (1)-(3). The PID has been tuned manually in this study. Initially the value of K_p was increased gradually and it had been observed that the actual value approaches the desired value. The process continues until the system started to oscillate and then the value of K_p was reduced to the value before the oscillation occurred. Then, the value of K_i was raised progressively until the system achieves the lowest steady state error and finally, K_d was increased steadily to improve the transient response.

In this simulation, it is desired for the system to achieve less than 5% percentage overshoot, settling time to be not more than 0.5 s and steady state error should be lower than 5%. Figure 5 shows the system without the any tracking controller implemented. The red line indicated the desired output while the green line shows the simulated output. From the result, the system does not meet the design requirement when it is not under any controller, where the percentage overshoot is 8% and the settling time is more than 0.5 s.

The system response meets all the design requirements with the implementation of the PID controller as can be observed in Figure 6. The red line indicated the desired output while the green line shows the simulated output. The value of the controller parameters has been tuned to K_p=87, K_i=5 and K_d=7. From the figure, it can be deduced that the system achieves a settling time of 0.15 s, percentage overshoot is 0.8 % and zero steady state error. Therefore, the same PID controller and tuning method is applied in the hardware experimental test with the physical master and slave subsystems of the tele-operated rehabilitation robot as described in the next subsection.

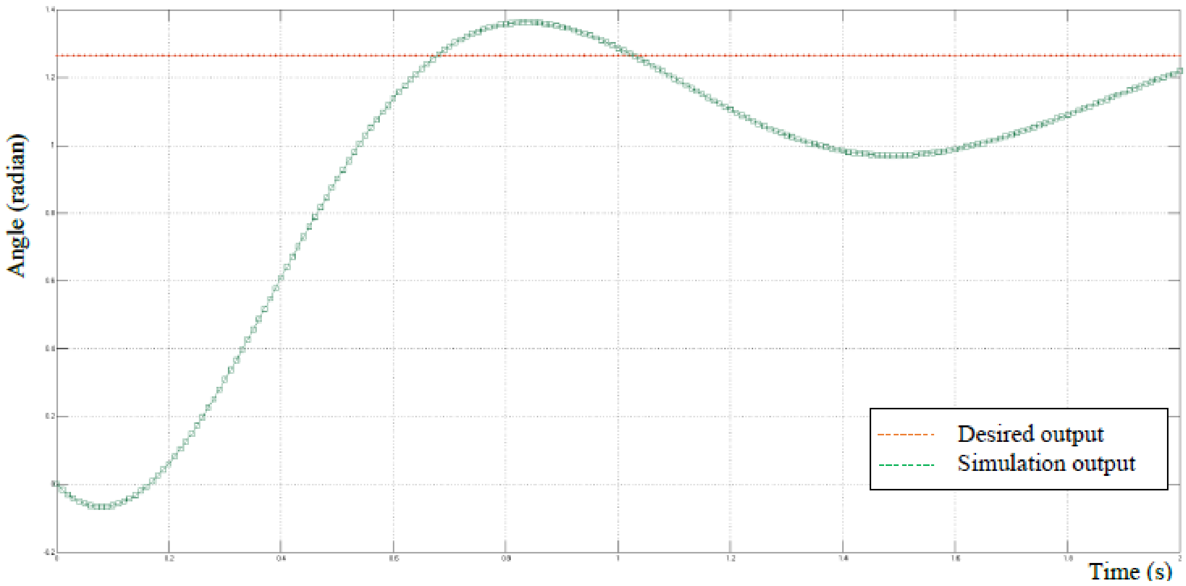

Figure 5. System response of the slave robot without any controller

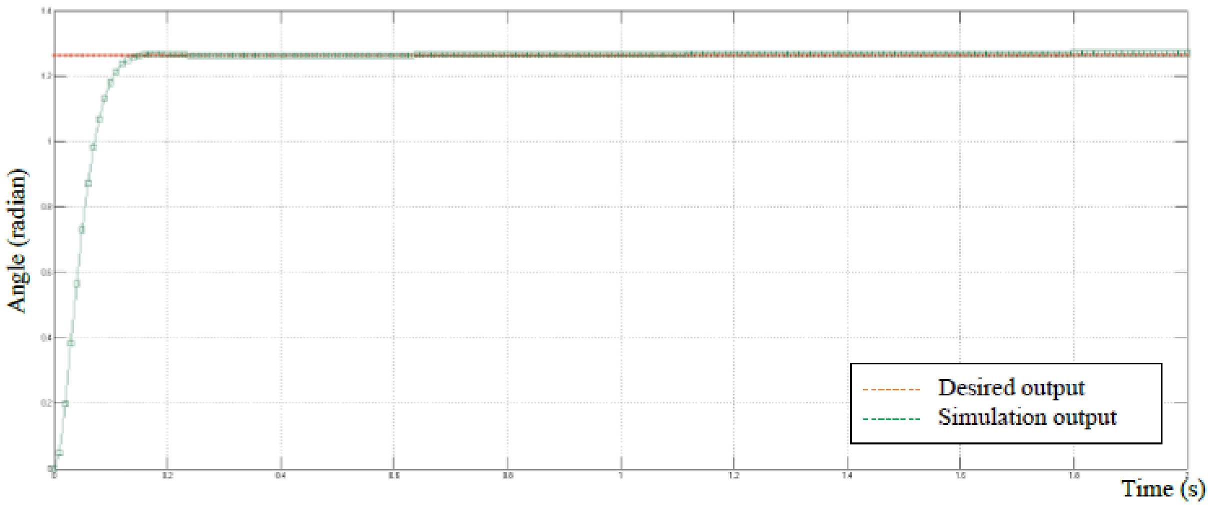

Figure 6. System response of the slave robot under PID controller

5.2 Hardware Experimental Test

Hardware experimental tests have been conducted using the complete prototype as shown in Figure 1. The system response under the PID controller and control parameters K_p=7, K_i=2 and K_d=1 is depicted in Figure 7. The blue line represents the movement of the master robot's wrist rest and the orange line shows the motion of the slave robot's counterpart. It is evident from the results that the slave robot that is attached to the patient's forearm tracks the master robot's motion trajectory that is provided by the therapist. However, the percentage overshoot, settling time, steady state error and time delay between the master and slave robot are high and need to be improved. The value of the steady state error with this choice of control parameters has been obtained to be 17%. A high percentage overshoot is greatly undesirable in this application as it may cause injuries and discomfort to the patients. Figure 8 shows the system response with K_p=5, K_i=7 and K_d=3. It can also be observed that the slave still tracks the master's trajectory and with a lower steady state error of 8 %. The system reaches a percentage overshoot of 22% and 0.8 s settling time. The best experimental test result is obtained when the controller parameters are tuned to K_p=5, K_i=10 and K_d=3 as shown in Figure 9, where the slave robot tracks the master robot even closer. The resulted steady state error under these PID control gains is 4 %, the percentage overshoot is obtained as 17% and the settling time is 0.7 s. At this stage of study, the time delay between the master and slave robots is 0.1 s.

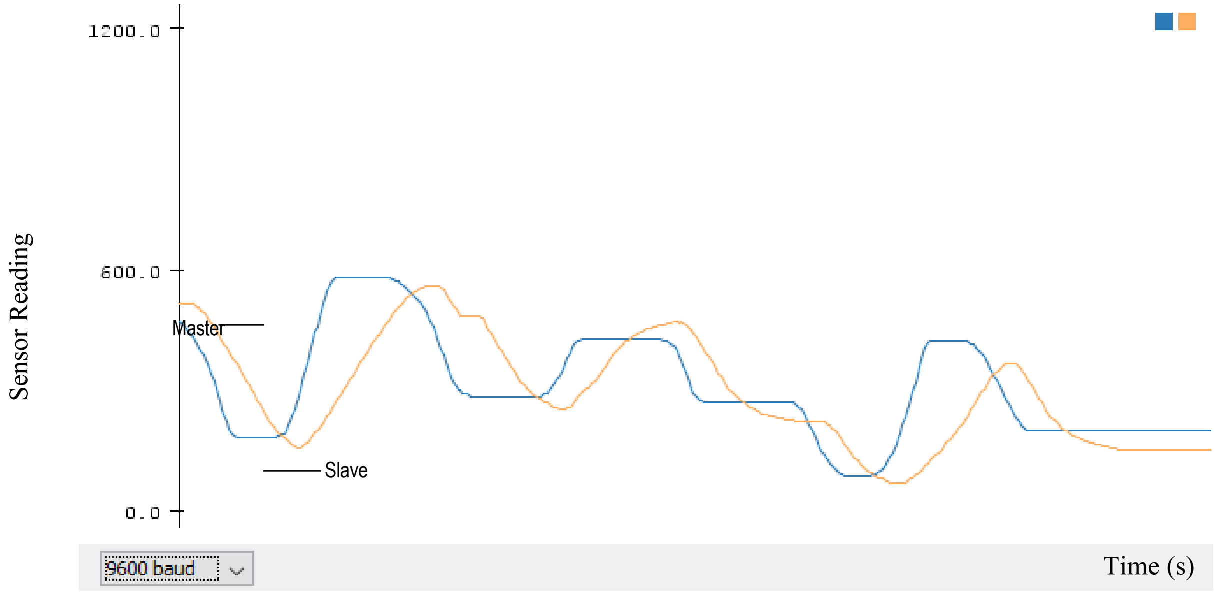

Figure 7. Hardware experimental test results under PID controller, where K*p*=7,K*i*=2 and K*d*=1

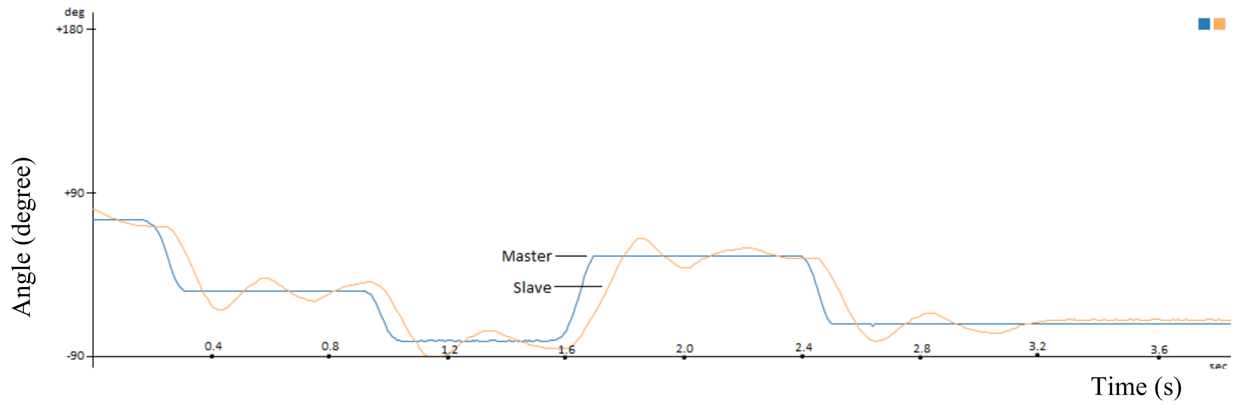

Figure 8. Hardware experimental test results with PID controller, where K*p*=5, K*i*=7 and K*d*=3

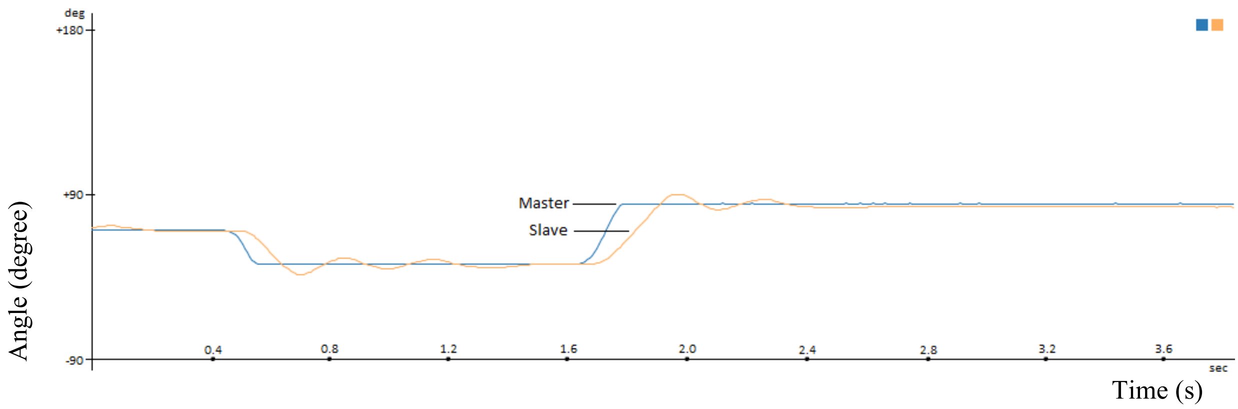

Figure 9. Hardware experimental test result with PID controller where, K*p*=5, K*i*=10 and K*d*=3

5.3 Discussion

From the test results, the developed tele-operated rehabilitation robot for forearm pronation/ supination in home-based therapy has successfully achieved its main objective, where the slave robot follows that the master robot's movement as evident in Figures 7-9. The implementation of the PID controller with a proper values of controller parameters improves the slave robot's performance in tracking the master robot's trajectory. With a proper choice of K_p , K_i and K_d values, the percentage overshoot and steady state error in the slave robot's response can be reduced.

At the current stage of study, the hardware experimental tests have been conducted in the same building, on the same floor to check the feasibility of the tele-operated robot in performing the master-slave based rehabilitation therapy. However, a more advanced devices and settings for long distance communication between the master and slave robots are necessary and tests need to be conducted in an actual home and hospital arrangement to ensure the effectiveness of the proposed home-based rehabilitation therapy. In this study also, the model of the robot has been approximated as a flywheel model. However, the model of human hand with multiple parameters and variations between patients have not been considered in constructing the mathematical model of the master-slave system. Therefore, a more accurate model that considers these factors and a more advanced controller to compensate for these uncertainties are vital to improve the performance of the tele-operated rehabilitation robot, especially in reducing the percentage overshoot since it is highly unwanted to guarantee patients' comfort and avoid injuries. A Graphical User Interface (GUI) also needs to be incorporated into the design to enable the doctors to monitor the patients' progress from the hospitals for the home-based rehabilitation treatment.

6.0 CONCLUSION

A tele-operated rehabilitation robot for forearm pronation and supination for home-based treatment has been presented in this paper. The robot has been developed based on the master-slave design, where the slave robot's movement is controlled by the master robot using ethernet. A low-cost Arduino microcontroller board has been used to reduce the overall cost and system complexity. The hardware experimental results verify that the proposed system has successfully fulfilled its main task, in which the slave robot on the patient's side follows the movement of the master robot, moved by the therapist. The performance of the robot has been improved with the application of a PID controller with a proper set of controller parameters. The highly undesirable overshoot and steady state error have been reduced under the controller. The developed tele-operated rehabilitation robot will enable the rehabilitation therapies to be conducted from the comfort of patient's home. This will facilitate the patients, especially those with a low mobility to get a proper treatment and reduce the caregiver's difficulties in managing them. The proposed system will also reduce the patient's travelling cost and time to the hospitals and rehabilitation centres to get the treatment. All these factors will reduce the number of skipped therapies, increase the recuperation rate, reduce the recovery time and help the patients to gain their original upper limb functions. For future works, focus will be given in reducing the time delay between the master and slave robots' motions. The communication device for long distances between the master and slave need to be incorporated in the tele-rehabilitation robot hardware and tests must be conducted to access its performance in a real hospital and home setting. The model of human upper limb needs to be considered in the robot's mathematical model and a more advanced controller needs to be formulated to solve the variations and uncertainties in the robot and human arm parameters. A Graphical User Interface (GUI) will be developed to allow the health providers to monitor the patients' progress in the remote therapy environment.

7.0 ACKNOWLEDGEMENT

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