Experimental Test on Rehabilitation Robot Manipulator Upper Limb with Impedance Control for Flexion-Extension Path Following Motion

Ade H. Sumarso, Augie Widyotriatmo, and Andri Pratama

***Abstract*— This research presents position and torque control with impedance scheme for a rehabilitation robot for post-stroke patients. A three-degree of freedom robot manipulator is developed in this research. The developed rehabilitation robot for patients after stroke period focuses on upper limb body to perform flexion-extension movements on a shoulder. Impedance scheme is derived from two inputs, external force and impedance values. External force is obtained by load cells placed at the end of the robot's end-effector. The external forces are measured in X and Y axis. The result is implemented for robot control system by applying PI controllers. Each parameter is utilized to control rotation movements and torque error in each X-axis and Y-axis motor. According to the test result, one-degree error is obtained. Robot movement is generated by planning the path movement before the rehabilitation. From the design and experiment, when a subject is unable to follow the path rehabilitation planning, it generates some force which is detected by force censor at the end-effector. This force gives the feedback signal to the motor. It allows motor to move in suitable directions and forces according to the signal at the end-effector. If external force does not exist, robot responses to assist the subject/patients by correcting the path planning. In the control system performance test, system error value of ± 1° was successfully obtained.**

***Index Terms*— Robot manipulator, End effector, Externals force, Impedance scheme, PI controller.**

I. Introduction

REHABILITATION robotic, including planar robotic, exoskeleton robotic and manipulator robotic, has attract attention of many researchers [1-3]. Planar robotic moves in one planar pathway. This robot is limited in terms of its movement. The other form of rehabilitation robot is exoskeleton robot which is used in the body of patient [4]. The weight of robot present unnecessary load to the patient. The third model is manipulator robot. The manipulator robot is able to interact with the patient. It is also possible to use the robot at several places in the human body.

During rehabilitation, the force which is given by the patient is an important component to predict the movement ability of stroke patient [6]. Some researchers observed the value of torque in rehabilitation robot. One of research control the torque according to the current [7]. In this research, the system was unable to read the motor direction, so an additional sensor is required. Torque adjustment is necessary during rehabilitation process [8]. Some rehabilitation movement is also developed with trajectory approach. In this method, a robot performs rehabilitation process in the different position according to the time and position [9]. Trajectory approach based on time might enforce muscle to follow the trajectory. The purpose of rehabilitation is to train the patient without any enforcement. So, the enforcement is unsuitable for post-stroke patient. Another method is adaptive trajectory [10]. In this method, compliant movement is created when the patient is out of desire position. However, undesired enforcement also appears during the rehabilitation.

In this present research, path following movement model is developed. Path following movement is a pattern that have to be followed by the patients without any time intervention. Robot is controlled based on impedance with load cell as a sensor. The force value and direction is provided by the sensors. While The subject movement is not appropriate to follow the path planning, sit will be a measured force by the force sensor at the end effector, thus increased force can give feedback to torque motor to make the compliant motor (motor moves according to the value and direction of the measured force). Furthermore, if there is no measured force at the end effector robot, the system will help objects to improve the following path.

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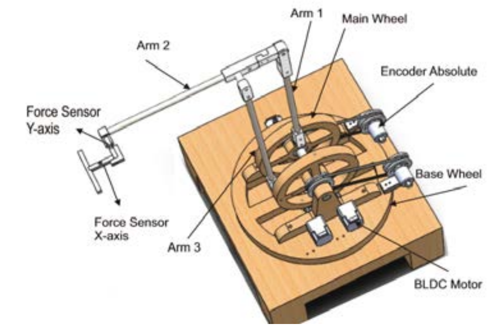

Fig. 1. Robot Model.

II. MODEL ROBOT'S DESIGN SYSTEM

A. Rehabilitation Robot Model

A three-degree of freedom rehabilitation robot is developed in this research. Wood material is used as the wheel and the base. Two motors are placed at main wheel and one motor is placed at the base.

Position is detected by absolute encoders while force is monitored by two load cells which are placed in the end of robot. The load cell is employed to read the amount and the direction of force in the two axis x-y. Experiment robot parameter is described at Table 1.

TABLE I
DIMENSION AND PARAMETERS ROBOTS

Parameter	Value
Base wheel	Ø 0.55 m
Main wheel	Ø 0.3 m
Wheel mass 1	5.75 kg
Wheel mass 1	1.10 kg
Inertia 1	0.218 Kg. m^2
Inertia 2	0.02 Kg. m^2
Inertia 3	0.02 Kg. m^2
Link arm 1	0.5 m
Link arm 2	0.5 m
Link arm 3	0.65 m
Gravitation	9.8 m / s^2

B. Robot Impedance Control Model

According to the dynamic equation in the previous paper [1], when external force is founded then external force equation can be described as (1).

$$M_q(\ddot{q}) + C_q(\dot{q}) + N_q(q) = \tau_r + F_e l_R. \quad (1)$$

where M_q is inertia mass, C_q is centrifuge coefficient, and N_q is gravity compensation. F_e l_R is subject external force times by motor torque (Nm). Equation (1) can be also written in the form (2).

$$\tau_r = M_q(\ddot{q}) + C_q(\dot{q}) + N_q(q) - F_e l_R \quad (2)$$

Motor torque equation is expressed as impedance characteristics equation by Hogan [2]. It can be seen in the Fig. 2 and written in the equation (3).

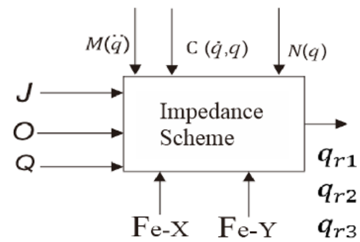

Fig. 2. Impedance Schema.

$$J(\ddot{q}_d - \ddot{q}_i) + O(\dot{q}_d - \dot{q}_i) + Q(q_d - q_i) = \tau_e \quad (3)$$

where $\ddot{q}_d, \dot{q}_d$, and q_d represent desired acceleration path, desired angular velocity path dan desired angular position path, respectively. $J, O,$ and Q indicate inertia, dumping dan spring coefficients, respectively. τ_e indicates torque, which is given by system to the subject, According to the equation (3) and (2) then system equation can be written in (4).

$$\tau_m = \tau_r + \tau_e - ((J(\ddot{q}_d - \ddot{q}_i) + O(\dot{q}_d - \dot{q}_i + Q(q_d - q_i)) + PI \quad (4)$$

where τ_m that is resulted from impedance scheme directly proportional to the desired rehabilitation (q_{r1}, q_{r2}, q_{r3}) which is continuously changing according to external force (F_e-X, F_e-Y) and given impedance value to the system. Next, controller P_i error between desired rehabilitation and actual robot angle. Controller produce PWM signal which is represented as a value of 0 ≤ PWM ≤ 255. *PI* controller is expressed as an equation (5).

$$0 = K_P e_q + \frac{K_P}{T_i} \int e_q \, dt \quad (5)$$

The above equation shows that error value of e_q will approach 0 when t approaches infinity. *PI* controller has optimum parameter when time and error have small value subject to applied controller, sensor and actuator ability. In order to apply optimum parameter, R subjective function of system is expressed in the equation (6).

$$R = \int_0^{\infty} e^2 \, dt \quad (6)$$

Mathematically, K_p and T_i optimum parameter of controller *PI* can be determined by assigning the minimum of R as a subjective function in the equation (7) which is the total of quadratic error value or the squared area under the curve of the first-order error equation.

$$\underset{K_p, T_i}{Min} R \quad (7)$$

$$\textit{Subject to} \quad M_q(\ddot{q}) + C_q(\dot{q}) + N_q(q) = \tau_r + F_e l_R$$

with the limit of permitted K_p dan T_i subject to the ability of robot system that is expressed by $N_q \leq K_p, T_i \leq \tau_{m_{max}}$, where N_q is the gravity compensation of robot dan $\tau_{m_{max}}$ is the maximum torque limit of motor.

III. EXPERIMENT AND RESULT

A. Robot System Architecture

The control implementation of the robot follows the control design in previous studies [1]. The system parameters are presented in Table 1, and the control system architecture is presented in Fig. 3.

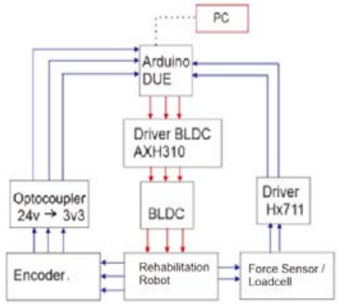

Fig. 3. Control System Architecture.

The system consists of three BLDC motors as actuators, three absolute encoders as position sensors, two load cells as external force sensors at the tip of the robot, and a microcontroller. An optocoupler is used as a voltage separator. The output of the load cell is millivolts signal so a Hx711 driver is needed as a signal amplifier so that it can be processed by the microcontroller.

B. Range of Motion

The work area of a robot (range of motion) is the total volume of the workspace that can be reached by the end effector (the tip of the robot) when the robot performs all possible movements. The work area is limited by the arrangement and types of joints contained in a robot, and the robot's geometry. (Sponge et al, 2008).

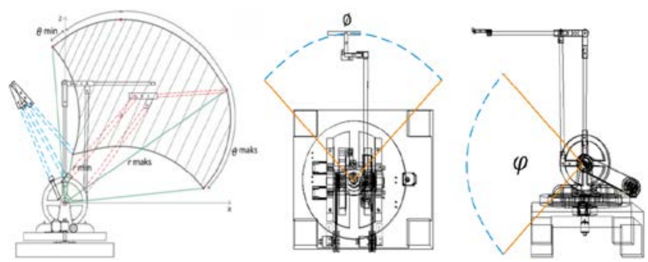

Fig. 4. ROM of Rehabilitation Robot.

The size of r_{min} can be determined by the *cosine* rule equation as follows:

$$r_{min}^2 = (L_1 + r_2)^2 + (L_2)^2 - 2\,(L_1 + r_2)\,(L_2)\cos 135° \qquad (8)$$

$$r_{min}^2 = (0.15+0.5)^2+(0.5)^2 - 2\,(0.15+0.5)\,(0.5)\,(-0.707)$$
$$r_{min} = 0.332\ m \approx\ 332\ mm$$

The size of r_{max} is:

$$r_{max}^2 = (L_1 + r_2)^2 + (L_2)^2 - 2\,(L_1 + r_2)(L_2)\cos 30° \qquad (9)$$

$$r_{max}^2 = (0.15+0.5)^2+(0.5)^2 - 2\,(0.15+0.5)\,(0.5)\,(0.866)$$
$$r_{max} = 1.102\ m \approx 1102\ mm$$

From Fig. 4, the work area of the robot has radius between $332 \leq r \leq 1102$. The range value of theta angle and azimuth angle are $0 \leq \varphi \leq 90$ and $45 \leq \emptyset \leq 135$, respectively.

Fig. 5. Flexion-Extension Movement Scenarios.

A. Experimental Test

The experimental test on the robot is performed by doing flexion-extension movements by healthy people with two motion scenarios. The first scenario is assumed as normal subject movement, while the second scenario is assumed as the rehabilitation patient's movement. Fig. 5 presents the testing of robot rehabilitation.

In the first scenario, the normal subject performed the flexion-extension movements three times in 50 seconds (Fig. 6). This assumes that the subject has no difficulty while doing flexion-extension movements.

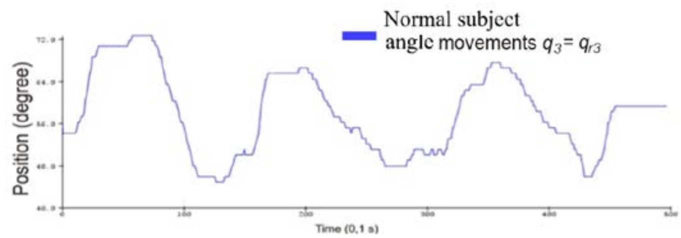

Fig. 6. Normal Subject Scenarios Movements.

In the second scenario, the subject movement is slower and fewer, assuming the subject has difficulty while doing flexion-extension movements. The rehabilitation subjects only made 1.5 times flexion-extension movements in 50 seconds. Fig. 7 presents the result of the movement in the second scenario.

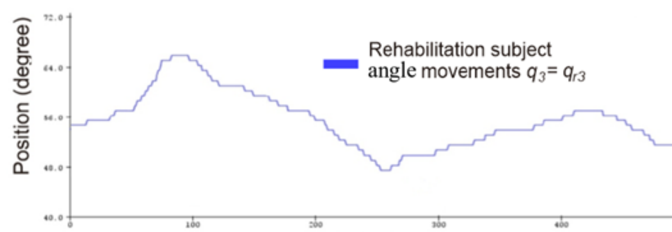

Fig. 7. Rehabilitation Subject Scenarios Movements.

From the rehabilitation movements in both scenarios, the force magnitude is obtained by the force sensor. In the second scenario, the detected force is larger than the first scenario. This is due to the assumption that the rehabilitation subjects have more rigid muscle so the exerted force to the system is greater. Fig. 8 illustrates the amount of external force exerted by the normal subjects to the robot.

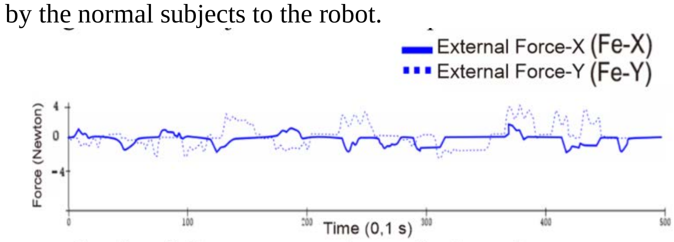

Fig. 8. Measured Force External in the First Scenario.

Fig. 9 shows the force magnitude on the rehabilitation subject. The force magnitude exerted on the robot cannot exceed the maximum force that the robot actuator able to accept.

Based on the specifications, the BLDC motor power used is 30 W. Assuming the minimum rotation of the robot motor is 60 RPM, the maximum torque value can be obtained by the following equation (10):

$$\tau = {(5252 \,.\, H_p)}/{RPM} \tag{10}$$

From the calculation equation (10) and assuming the rpm value is 60 rpm, the maximum torque value the robot is 3.518 N.m.

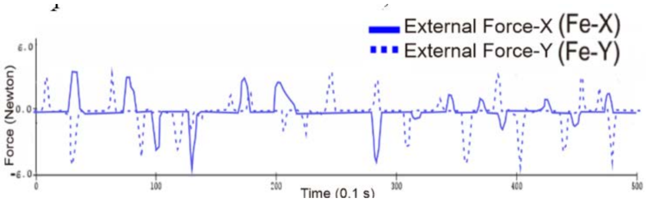

Fig. 9. Measured Force on the Second Scenario.

In this study, the impedance value given to the system is fixed. The impedance value is one robot inertia. The PI parameters in the implementation of each system are P_1= 0.6 Nm, P_2= 0.8 Nm dan T_{i1}= 200 Nm, T_{i2}= 200 Nm respectively. The angle position of end effector q_1 and q_2 is presented in Fig. 10. Fig. 11 presents the rehabilitation angle q_{r1} and q_{r2} based on the impedance robot model in Fig. (2). The rehabilitation angles q_{r1} and q_{r2} are dynamic setpoints and must be followed by the robot's angle position. Fig. 10 presents the angle position of the end effector q_1 and q_{r1} in the first scenario.

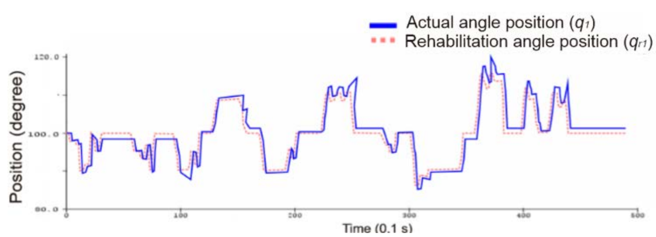

Fig. 10. The Angle Position of End Effector q_1 and q_{r1} in the First Scenario.

The rehabilitation angle magnitude varies due to the influence of external forces and the impedance value provided. The impedance regulation will make the robot follow the direction and force magnitude of the external force applied to the robot. Fig. 11 presents the angle position of the end effector q_2 and q_{r2} in the first scenario.

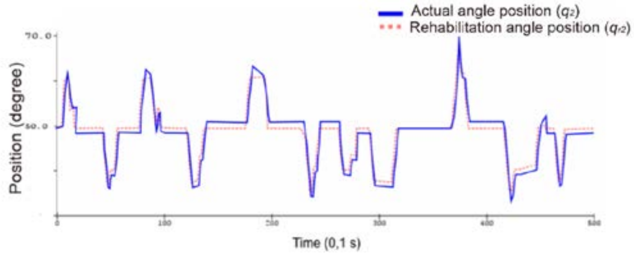

Fig. 11. The Angle Position of End Effector q_1 and q_{r1} in the First Scenario.

When the subject applied an external force to the robot system, the impedance control will make the robot follows the direction and the force magnitude of the external force. However, when there is no external force from the subject, the system will help the subject return to the desired position. The angle position of end effector q_1 and q_2 and the rehabilitation angle q_{r1} and q_{r2} in the second scenario are presented in Figs. 12 and 13 respectively.

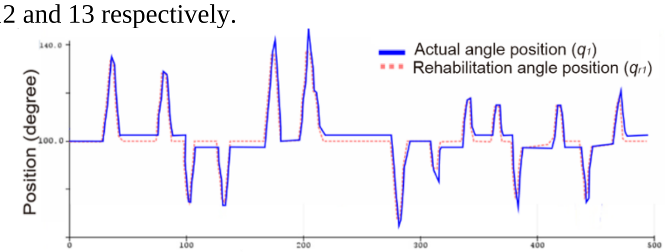

Fig. 12. The Angle Position of End Effector q_1 and q_{r1} in the Second Scenario.

From Fig. 12, the angle range achieved by the robot is greater than the angle range in the first scenario. This is due to the assumption that in the second scenario the external force exerted by the rehabilitation subject is large and the subject has more stiff muscle character compared to the healthy subjects.

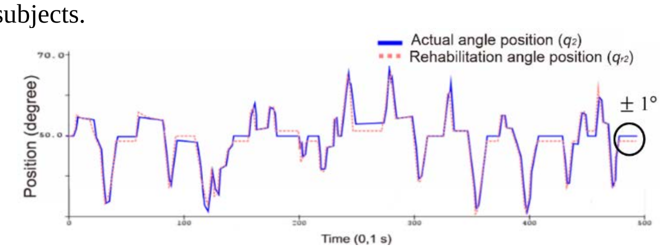

Fig. 13. The Angle Position of End effector q_2 and q_{r2} in the second scenario.

Overall system performance is represented in Fig. 13, where the system has an error value of ± 1°. This is due to the accumulation of errors, some factors may caused by the resolution of the position sensor, the backlash from the robot mechanic, and the performance of the controller.

The results of the error calculation by the PI controller will generate a PWM value. A PWM value is the amount of the voltage applied to the motor, based on the obtained error value. Fig. 14 presents the PWM data from controller calculations in the first scenario.

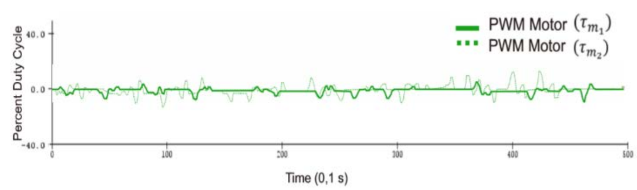

Fig. 14. PWM Data Results in the Second Scenario.

The greater the difference between the rehabilitation angle and the actual angle, the greater the PWM value given to the motor. Fig. 15 presents the PWM data value in the second scenario. The magnitude of the PWM value is represented from 0 to +255 due to the 8 bits size data controller. The robot system in this study has the smallest value from the total amount of PWM data. This is due to the characteristic of the rehabilitation robots. The rehabilitation robots have a slower movement compared to the industrial robots where the industrial robots are used for production activities.

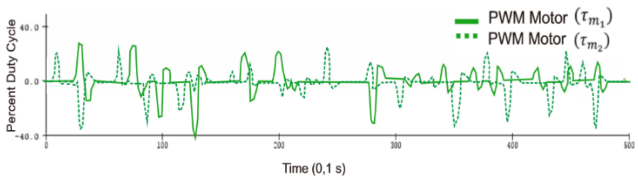

Fig. 15. PWM Data Results in the Second Scenario.

IV. Conclusion

In this paper, an experimental test with the proposed impedance scheme for healthy people has been carried out with the scenarios of healthy subjects and the rehabilitation subjects. The proposed impedance scheme is able to function properly. The control system performance test on the rehabilitation robot has been successfully carried out with an error value of the system ± 1°. The errors probably are due to the resolution of the position sensor, the backlash from the robot mechanic, and the performance of the controller. For further research, research involving medical personnel is needed to find out the suitable magnitude value for various types of rehabilitation patients.

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