Modeling and Design of Low Cost Lower Limb Rehabilitation Robot Control System for Post-Stroke Patient using PWM Controller

Herianto*, Widhi Yoga Saryanto, and Adha Imam Cahyadi

***Abstract*— Rehabilitation robot is a robot for assisting the patient to recover from stroke or other extremity injuries. As the number of post-stroke patients is increased, it needs more rehabilitation robot to support post-stroke patients. Generally, rehabilitation robots used for lower limb rehabilitation are highly priced and not affordable to the lower income segment of the population. This is caused by the application of the current control system that needs expensive hardware system. Therefore, we design the control system by using Pulse Width Modulation (PWM) controller. This paper presents the result of our research that aim to develop lower limb rehabilitation robot control system with a low price by using a PWM controller for voltage manipulation. The system model and hardware implementation have been built to show the effectiveness of the proposed system and to find the optimal conditions.**

***Index Term*— Rehabilitation Robots, Lower Extremities, Stroke, PWM Controller**

I. INTRODUCTION

A STROKE is a brain attack. It can happen to anyone at any time. It occurs when blood flow to an area of the brain is cut off. When this happens, brain cells are deprived of oxygen and begin to die. When brain cells die during a stroke, abilities controlled by that area of the brain, such as memory and muscle control are lost.

Each year, nearly 800.000 people experience a new or recurrent stroke in U.S. [1]. It means that a stroke happens every 40 seconds. Stroke is the fourth leading cause of death in the U.S. In Asian country, stroke is the second top cause of death. Indonesia is ranked first by the largest number of stroke patients in Asia now. In Indonesia, approximately 500,000 people every year suffered stroke, in which about 25% or 125,000 people died, and the rest have mild or severe disability [2]. Nowadays, the stroke becomes an important and urgent issue that must be handled.

How a person is affected by their stroke depends on where the stroke occurs in the brain and how much the brain is damaged. For example, someone who had a small stroke may only have minor problems such as temporary weakness of an arm or leg. Whereas, people who have larger strokes may be permanently paralyzed on one side of their body or lose their ability to speak. Some people recover completely from strokes, but more than 2/3 of survivors will have some type of disability.

Stroke rehabilitation is a recovery program for stroke conditions that aim to optimize physical capacity and functional ability of the post stroke patients. The goal of a stroke rehabilitation program is to help post-stroke patient relearn lost skills when stroke affected part of their limb. As the number of post-stroke patients are increased, it takes more physiotherapists to help post-stroke patients [3] [4]. Some physiotherapists used a manual method by giving movement action directly to the part of the body of the patient that affected by stroke attack. In fact, manual rehabilitation is not accurate and non repeatable. Moreover, it is tedious, and adds burdens to human therapists [5]. To help the rehabilitation process, a device is prepared to serve the rehabilitation operation. By using rehabilitation device, the rehabilitation of post-stroke patient can be done anytime and anyplace.

Rehabilitation robot is a robot for assisting the patient to recover from stroke or other extremity injury. The purpose of developing rehabilitation robot is to solve daily living problems in individual activities [6]. The ability of robots to deliver training with high capacity and repeatability makes them very valuable assistive tools to cater high quality treatment at a lower price and effort [7]. Herianto *et al*. have developed a robot to assist the rehabilitation of lower limbs. The robot was successfully designed and manufactured [8]. However, their research only focused on the design and manufacture of the robot. They did not integrate the control system in the robot. Potentiometers were used as a position sensor of the link, therefore an actuator speed and torque could not precisely control.

This study proposes and develops a rehabilitation robot that assist the rehabilitation of lower limb post stroke patients. This

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study focus on the development of the lower limbs rehabilitation robot due to lower limb is an important part of the body that play a role in the movement and activity of the body, especially walking. Rehabilitation robots are designed to assist foot rehabilitation passively on the knee and ankle.

Rehabilitation robot that was designed consisting of two-link manipulator. Link 1 assisted the rehabilitation of the knee and link 2 for the ankle. The task and function of the robot were equal to the CPM (Continuous Passive Motion) device, exercised passive motion of the joint (range of movement). Passive exercises are performed for the patient by another person or by an exercise device. This device is called robotic device or CPM. They are usually applied to patients who do not have muscle strength. Continuous Passive Motion (CPM) robots are widely applied in many medical centers for therapy and rehabilitation functions. The CPM concept was first introduced in the 1970s [9]. During the rehabilitation process, patients sometimes move their extremities suddenly due to reflexes. CPM robots do not respond in these kinds of situations and are hence not suitable for physical therapy.

A rehabilitation robot design usually employs a PID controller. This controller is the most popular type of controller than the other. PID controller is a controller type that most frequently practiced in industry [10]. Performance of PID controller can be accepted in most industrial processes easily [11]. PD controller [12] and PID can make a robot manipulator becomes stable in accordance with the desired set point [13] [14]. The research was preceded by a process modeling system to help determine the PID parameters according to the system. The modeling system aims to save time and costs. In addition, it is also aimed to minimize the damage to the robot in case of errors in terms of tuning PID parameters.

Two-links modeling has been investigated by researchers in the world. Manjeet and Khatri simulated the mass of particles with two arms [15]. Manjeet and Khantri study is based on PD and PID controller to control the two-link manipulator with manipulated variables, such as torque and signaling an error of position and velocity. From this study, we concluded that PD and PID control performed good tracking the position, but less good tracking the speed. This study only simulated the arm in the form of particle mass, even though almost robot was rigid body and flexible body. In this research there was no system implementation as well. Other modeling is performed by Goswami. He performed the simulation and implementation of single arm robot [16]. The four types of controllers, PD, PID, LQR and NN, have been compared to control the system. The result of controllers tested, that all controllers can control the angular position well.

Another study was conducted by David I Robles, who designed the PID controller to control the two-link robot arm [17]. Hashemipour et al took a study to compare between PID controller with sliding mode controller for controlling the two-link robot arm rigid body [18]. From this study, he found that the PID controller produces a better system response than a sliding mode controller.

Lower limb rehabilitation robots were developed to assist post stroke patients in their lower extremities. Akdogan *et al.* developed lower limb rehabilitation robot using impedance control [19]. Manipulator robot can perform all the active and passive exercises as well as to learn and perform certain specific movements. Mohammed et al. developed lower limb rehabilitation robot using input-output feedback linearization and model predictive control. The controller has shown good result in term of stability, robustness, and regulation with respect to external disturbances [20]. Madonski *et al.* developed an Active Disturbance Rejection Controller (ADRC) in governing a proper realization of basic limb rehabilitation trainings. By the use of the ADRC approach, the modeling uncertainty in the plant is partially decoupled from the system, which increases the robustness of the whole control framework against both internal and external disturbances [21]. Song et al. developed a dynamic model of post-stroke patient's arm into an impedance model and propose an adaptive controller, which consists of an adaptive PI control algorithm and adaptive damping control algorithm [22]. Research conducted by Song et al. is limited to the rehabilitation of the upper limbs.

In fact, the stroke patients are not only suffered by the prosperous people. It is needed a study to build a convenient device, cheap and affordable. This can be achieved by creating a simple control system. Riaan Stopforth has also tried to make rehabilitation lower limb exoskeleton with a cost of less than US $ 3.000 [23]. Controller and motor driver are two components that have to be considered. Arduino based microcontroller can be used due to the simplicity and the price. Motor driver that controls the voltage output to the motor is cheaper compared to the current mode.

Based on the above reality that stroke patients are not only prosperous people and the need to use simple hardware for the robot, in this study, we have developed and manufactured a low cost lower limb rehabilitation robot. We realized it by developing a device with Pulse Width Modulation (PWM) system. Generally, people use a current source to control the DC motor system. The current source system is comparatively expensive. Therefore, the voltage input source is used in this research to make the cheaper system. Thus, the robot can be built with worthy function and low price. The aim of this paper is to describe the design process and a control method of the low price lower limb rehabilitation robot by using PWM. The system model and hardware implementation have been built to show the effectiveness of the proposed system and to find the optimal conditions.

II. SYSTEM MODELLING

Figure 1 shows the model of rehabilitation robot. The model consists of two-link manipulator. Link 1 assisted the rehabilitation of the knee and link 2 for the ankle.

Rehabilitation robot dynamics with two-link manipulator can be modeled into a mathematical equation form. Kinetic energy is the energy of motion which is obtained as the movement of objects, particles, or a set of particles. In this study, the kinetic energy consists of kinetic energy of rotation and kinetic energy of translation that can be seen in equation (1) and (2).

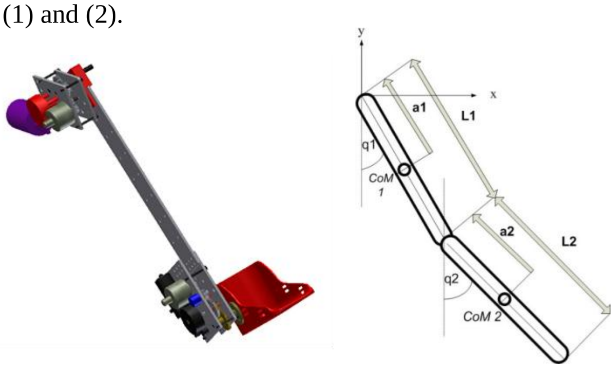

Fig. 1. Two DOF of Robot Model

$$T = \frac{1}{2}\, m\, v^2 \;+\; \frac{1}{2}\, J \dot{q}^2 \tag{1}$$

$$T = \frac{1}{2} m_1 a_1{}^2 \dot{q_1}^2 + \frac{1}{2}\; J_1 \dot{q_1}^2 + \frac{1}{2} m_2\, l_1{}^2 \dot{q_1}^2 + \frac{1}{2} m_2\, a_2{}^2 \dot{q_2}^2 + m_2\, l_1 a_2 \dot{q_1} \dot{q_2} \cos(q_1 - q_2) + \frac{1}{2}\; J_2 \dot{q_2}^2 \tag{2}$$

Potential energy of a rehabilitation robot with two-link manipulator can be written into the following equation.

$$V = -\, m_1\, g\, a_1 \cos q_1 - m_2\, g l_1 cos q_1 - m_2\, g a_2 cos q_2 \tag{3}$$

Based on kinetic energy (T) and potential energy (V), Lagrange equation can be composed as follows.

$$L = T - V$$

$$L = \left(\frac{1}{2} m_1 a_1{}^2 \dot{q_1}^2 + \frac{1}{2}\, J_1\, \dot{q_1}^2 + \frac{1}{2} m_2\, l_1{}^2 \dot{q_1}^2 + \frac{1}{2} m_2\, a_2{}^2 \dot{q_2}^2 + m_2\, l_1 a_2 \dot{q}_1 \dot{q}_2 \cos(q_1 - q_2) + \frac{1}{2}\; J_2 \dot{q}_2{}^2\right) + \; m_1\;\, g a_1 \cos q_1 + m_2\;\, g l_1\, cos\, q_1 + m_2\;\, g a_2\, cos q_2) \tag{4}$$

Equation 5 (Lagrange) was used to derive equation 4 to find equation of motion for each link.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}w}\right) - \frac{\partial L}{\partial qw} = 0 \tag{5}$$

By substituting 4 equation into 5 equation with $q_w = q_1$ then obtained,

$$\frac{\partial L}{\partial q1} = -m_2\, l_1 a_2\, \dot{q}_1\, \dot{q}_2 \sin(q_1 - q_2) - \; m_1\, g\, a_1 \sin q_1 - m_2\;\, g\, l_1 \sin q_1 \tag{6}$$

and for $q_w = q_2$ then obtained,

$$\frac{\partial L}{\partial q2} = m_2\;\, l_1\, a_2\, \dot{q}_1\, \dot{q}_2 \sin(q_1 - q_2) - \; m_2\;\, g a_2\, \sin q_2. \tag{7}$$

therefore, the equation of motion of the rehabilitation robot with two-link manipulator can be modeled into two mathematical equations as equation (8) and (9).

$$\left(m_1 a_1{}^2 + J_1 + m_2\, l_1{}^2\right)\ddot{q_1} + m_2\, l_1 a_2 \ddot{q_2} \cos(q_1 - q_2) - m_2\, l_1 a_2 \dot{q}_2 \sin(q_1 - q_2)\;(\dot{q}_1 - \dot{q}_2)\Big) - (-m_2\, l_1 a_2\, \dot{q}_1\, \dot{q}_2 \sin(q_1 - q_2) - \; m_1\; g\; a_1 \sin q_1 - m_2\;\, g\; l_1 \sin q_1) = \tau_1 \tag{8}$$

$$(m_2\; a_2{}^2 + J_2)\ddot{q_2} \;+ m_2\;\, l_1\; a2\; \ddot{q_1}\;\, \cos(q_1 - q_2) - m_2\; l_1\; a2\; \dot{q_1}\;\, \sin(q_1 - q_2)\;(\dot{q}_1 - \dot{q}_2)) - (m_2\; l_1\; a_2\; \dot{q}_1\; \dot{q}_2 \sin(q_1 - q_2) - \; m_2\;\, g\; a_2\;\, \sin q_2) = \tau_2 \tag{9}$$

From equation (8) and (9), equations of motion can be rewritten into a matrix form as shown in equation (10) and (11).

$$\tau = B(Q)\big(\ddot{Q}\big) + C\big(\dot{Q}, Q\big) + G(Q) \tag{10}$$

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix}(m_1 a_1{}^2 + J_1 + m_2 l_1{}^2) & m_2 l_1 a_2 \cos(q_1 - q_2)\\ m_2\; l1 a_2 \cos(q_1 - q_2) & (m_2\; a_2{}^2 + J_2)\end{bmatrix}\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix} + \begin{bmatrix}-m_2\; l_1 a_2 \dot{q}_2 \sin(q_1 - q_2)\;(\dot{q}_1 - \dot{q}_2)\\ -m_2 l_1 a_2 \dot{q}_1 \sin(q_1 - q_2)\,(\dot{q}_1 - \dot{q}_2) - m_2 l_1 a_2 \dot{q}_1 \dot{q}_2 \sin(q_1 - q_2)\end{bmatrix} + \begin{bmatrix}m_1\; g\; a_1 \sin q_1 + \; m_2\;\, g\; l_1 \sin q_1\\ m_2\;\, g\; a_2\;\, \sin q_2\end{bmatrix} \tag{11}$$

III. CONTROL SYSTEM

A. Voltage to Torque Transformation

Rehabilitation robot motion expressed by equation 12.

$$\tau = B(Q)\ddot{Q} + C\big(\dot{Q}, Q\big) + G(Q). \tag{12}$$

This (12) can be written in another form as shown in equation 13.

$$\ddot{Q} = B(Q)^{-1}\big[-C\big(\dot{Q}, Q\big) - G(Q)\big] + B(Q)^{-1}\boldsymbol{\tau}. \tag{13}$$

In (13), the input form is torque. The torque of the permanent magnet motor is essentially proportional to the current.

$$\tau\,(s) = K_t\, I_a(s). \tag{14}$$

However, the current source is difficult to be applied to this system. It is also comparatively expensive. Therefore, the voltage input source is used in this study. The voltage disposition be done by adjusting the duty cycle (the signal from the PWM). However, the use of voltage (PWM signal) as input can make the system more complex in modeling. In (15), the equation of permanent magnet motor torque (τ) at steady state condition can be determined.

$$\tau = -\frac{K_b K_t}{R_a}\omega_m + \frac{K_t}{R_a}V \qquad (15)$$

The ω_m Is the rotational speed of the motor, and V is the voltage input (PWM signal). If the motor speed is equal to 0 (ω_m = 0) then $\tau = \tau_{stall}$ means the maximum torque can be issued by the motor until the motor can stop.

$$\tau_{stall} = \frac{K_t}{R_a}V \; ; \frac{K_t}{R_a} = A_1 \; ; \tau_{stall} = A_1 \; V \qquad (16)$$

A_1 is the gradient of the torque to voltage for each duty cycle (PWM). This gradient can be known through experimentation. In other cases, if the motor rotates without the load, the torque (τ) equal to 0.

$$0 = \frac{K_t}{R_a}\left(V - K_b\,\omega_m\right)$$

$$\omega_{no-load} = \frac{V}{K_b} \qquad (17)$$

$$V = Kb\;\omega_{no-load} \;\; ; Kb = A_2 \; ; V = A_2 \;\; \omega_{no-load} \qquad (18)$$

A_2 is the gradient of voltage to $\omega_{no-load}$, with y axis is voltage and x axis is $\omega_{no-load}$. The transformation process of the voltage to the torque can be modeled into (19).

$$\tau = -A_1 A_2 \dot{q} + A_1 V \qquad (19)$$

B. *PID Control*

PID control system block of our system can be seen in Figure 2. Voltage to Torque controller is used in our system due to the easiness and inexpensive one.

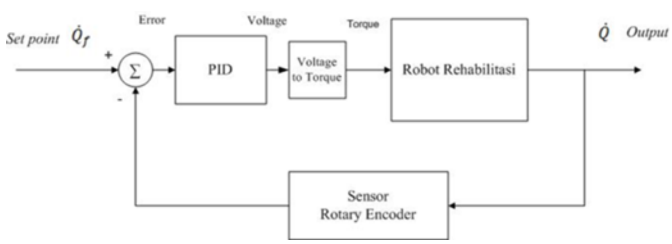

Fig. 2. PID Control System Block

The error of the system can be expressed by the equation (20).

$$e(q_1) = \dot{q}_{1f} - \dot{q}_1 ; e(q_2) = \dot{q}_{2f} - \dot{q}_2 \qquad (20)$$

$\dot{q}_{1f}$ and $\dot{q}_{2f}$ are the angular velocity set point of arm 1 and arm 2. $\dot{q}_1$ and $\dot{q}_2$ are the angular velocity of arm 1 and arm 2. In general, the manipulating variable for the PID controller can be written as (21).

$$MV\,(t) = K_p e\,(t) + K_i \int e\,(t)\,dt + K_d\,\frac{de\,(t)}{dt} \qquad (21)$$

For this speed control system, the control voltage can be written as (22).

$$V_{PID} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} K_{p1}.e(q_1) + K_{d1}.\dot{e}(q_1) + K_{i1}\int_0^t e(q_1)\,dz \\ K_{p2}.e(q_2) + K_{d2}.\dot{e}(q_2) + K_{i2}\int_0^t e(q_2)dz \end{bmatrix} \qquad (22)$$

So that the whole system of PID control can be run through simulation, the dummy state x_1 and x_2 is used as the integral rate in (22).

$$V_{PID} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} K_{p1}.(\dot{q}_{1f} - \dot{q}_1) - K_{d1}.(\ddot{q}_1) + K_{i1}.x_1 \\ K_{p2}.(\dot{q}_{2f} - \dot{q}_2) - K_{d2}.(\ddot{q}_2) + K_{i2}.x_2 \end{bmatrix} \qquad (23)$$

Where

$$\dot{x_d} = \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} \dot{q}_{1f} - \dot{q}_1 \\ \dot{q}_{2f} - \dot{q}_2 \end{bmatrix} \qquad (24)$$

The (23) can be simplified as (25)

$$V_{PID} = [K_p.(\dot{Q}_f - \dot{Q}) - K_d.(\ddot{Q}) + K_i.x_d] \qquad (25)$$

The voltage is then converted to torque dependent on the speed of the link as (26).

$$\tau_{PID} = -A_1 A_2 \dot{Q} + A_1 V_{PID};$$

$$\tau_{PID} = -A_1 A_2 \dot{Q} + A_1[K_p.(\dot{Q}_f - \dot{Q}) - K_d.(\ddot{Q}) + K_i.x_d] \quad (26)$$

The total torque in the system is a superposition of the torque control with the torque due to friction (27).

$$\tau = \tau_{PID} + \tau_{fr} \qquad (27)$$

The τ_{fr} is the torque from the friction.

$$\tau_{fr} = \begin{bmatrix} \tau_{f\,L1} \\ \tau_{f\,L2} \end{bmatrix} \qquad (28)$$

The $\ddot{q}$ The variable can be written as (29).

$$\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} = -B(Q)^{-1}\left(C(\dot{Q},Q) + G(Q)\right) + B(Q)^{-1}[-A_1 A_2 \dot{Q} + A_1[K_p.(\dot{Q}_f - \dot{Q}) - K_d.(\ddot{Q}) + K_i.x_d]] + B(Q)^{-1}\boldsymbol{\tau_{fr}} \qquad (29)$$

In order to run in the simulation, the equation (29) must be rearranged into equation (30) by separating $\ddot{q}$.

$$\ddot{q} = B(Q)^{-1}(\boldsymbol{\tau}_{PI} + \boldsymbol{\tau}_{fr}) - B(Q)^{-1}A_1K_d\ddot{Q} - B(Q)^{-1}\left(C(\dot{Q},Q) + G(Q)\right) \tag{30}$$

where

$$\tau_{PI} = -A_1A_2\dot{Q} + A_1[K_p.(\dot{Q}_f - \dot{Q}) + K_i.x_d] \tag{31}$$

$$K_d = \begin{bmatrix} K_{d1} & 0 \\ 0 & K_{d2} \end{bmatrix} \tag{32}$$

Therefore, the equation can be written as (33) and (34):

$$[I + B(Q)^{-1}A_1K_d]\ddot{Q} = B(Q)^{-1}(\tau_{PI} + \boldsymbol{\tau}_{fr}) - B(Q)^{-1}\left(C(\dot{Q},Q) + G(Q)\right) \tag{33}$$

$$\ddot{Q} = [I + B(Q)^{-1}A_1K_d]^{-1}B(Q)^{-1}\left(\tau_{PI} + \boldsymbol{\tau}_{fr} - \left(C(\dot{Q},Q) + G(Q)\right)\right) \tag{34}$$

The (34) equation can be written as state space equation. The state variable is *x*.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} = \begin{bmatrix} \int_0^t\left(\dot{q}_{1f} - \dot{q}_1\,(z)\right)d\,z \\ \int_0^t\left(\dot{q}_{2f} - \dot{q}_2(z)\right)\,d\,z \\ q_1 \\ q_2 \\ \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \tag{35}$$

For the simulation, the overall speed control system equation can be written as the following state space equation

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \begin{bmatrix} \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \dot{q}_{1f} - x_5 \\ \dot{q}_{2f} - x_6 \\ x_5 \\ x_6 \\ [I + B(x)^{-1}A_1K_d]^{-1}B(x)^{-1}\left(\tau_{PI}(x) + \tau_{fr} - \left(C(x) + G(x)\right)\right) \end{bmatrix} \tag{36}$$

$$\tau_{PI}(x) = -A_1A_2\begin{bmatrix} x_5 \\ x_6 \end{bmatrix} + A_1\left[K_p.\left(\dot{q}_f - \begin{bmatrix} x_5 \\ x_6 \end{bmatrix}\right) + K_i.\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}\right] \tag{37}$$

$$K_d = \begin{bmatrix} K_{d1} & 0 \\ 0 & K_{d2} \end{bmatrix} \tag{38}$$

$$B(x) = \begin{bmatrix} (m_1{a_1}^2 + J_1 + m2{l_1}^2) & m_2\,l_1a_2\cos(x_3 - x_4) \\ m_2\,l1a_2\cos(x_3 - x_4) & (m_2\,{a_2}^2 + J_2) \end{bmatrix} \tag{39}$$

$$C(x) = \begin{bmatrix} -m_2\,l_1a_2x_6\sin(x_3 - x_4)\,(x_5 - x_6) \\ -m_2l_1a_2x_5\sin(x_3 - x_4)\,(x_5 - x_6) - m_2l_1a_2x_5x_6\sin(x_3 - x_4) \end{bmatrix} \tag{40}$$

$$G(x) = \begin{bmatrix} m_1\,g\,a_1\sin x_3 + m_2\;g\,l_1\sin x_3 \\ m_2\;g\,a_2\;\sin x_4 \end{bmatrix} \tag{41}$$

IV. EXPERIMENTAL MODEL

Figure 3 explains the experimental setup for implementing the proposed system. Arduino Mega is used as a controller. Autonics Incremental rotary encoder (type E50S8-3600-3-N-24) is employed to measure the velocity of the link. Driver EMS 30 A H-Bridge is used as a DC motor driver.

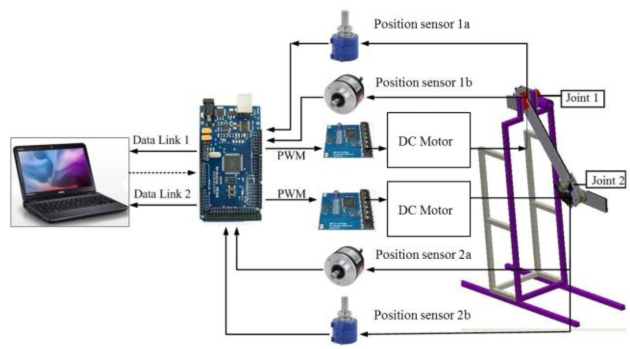

Fig. 3. Experimental Setup

Mechanical system of the model as shown in the Figure 3 has a joint specification explained in Table 1. Gearbox has been used for increasing the torque by converting velocity into torque.

Table I
Joint Specification

Joint	Range of Motion (°)	Maximum Torque (Nm)	Maximum velocity (rpm)
1	0 - 130	81.6	17
2	0 - 60	22	13.6

The system model and hardware implementation have been built to show the effectiveness of the proposed system and to find the optimal conditions. Based on PID control model, we need parameter *A1* and *A2*. A_1 and A_2 are constants related to the properties of DC motor. The torque (τ) value is obtained from the value of the voltage in the form of Pulse Width Modulation. This voltage is a signal control of this speed control system.

Based on the design of control that has been made, the parameter *A1* and *A2* can be defined through experimentation.

Stall Torque to voltage relationship of link 1 (A_1 of link 1) can be seen in Fig. 4. In this figure, it is known that the gradient between Stall Torque to voltage is equal to 8.2705. Graph Voltage against $\omega_{no-load}$ of link 1 (A_2 link 1) is shown in Figure 5. The gradient between voltage to $\omega_{no-load}$ voltage is equal to 2.6063. Stall Torque to voltage relationship of link 2 (A_1 of link 2) can be seen in Fig. 6. In this figure, it is known that the gradient between Stall Torque to voltage is equal to 2.5737. Graph Voltage against $\omega_{no-load}$ of link 2 (A_2 link 2) is shown in Figure 7. The gradient between voltage to $\omega_{no-load}$ voltage is equal to 4.8531.

Then, the model was implemented to the hardware to analyze effectiveness of the system. Simulation on the computer was done before implemented to the real hardware to avoid undesired condition.

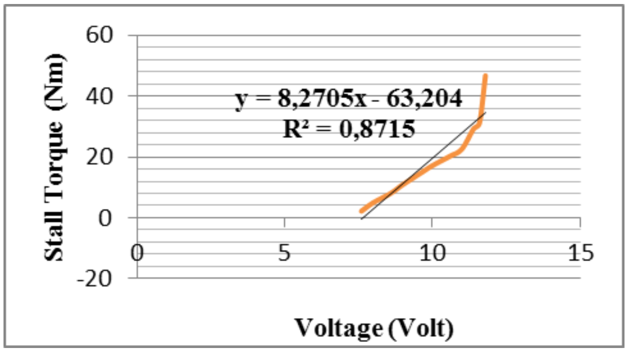

Fig. 4. Stall Torque to voltage relationship of link 1

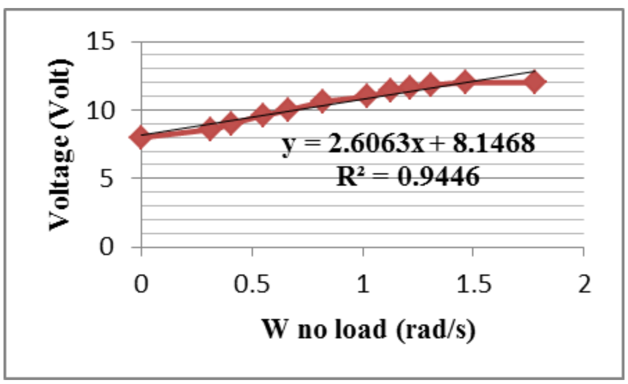

Fig. 5. Voltage to $\omega_{no-load}$ relationship of link 1

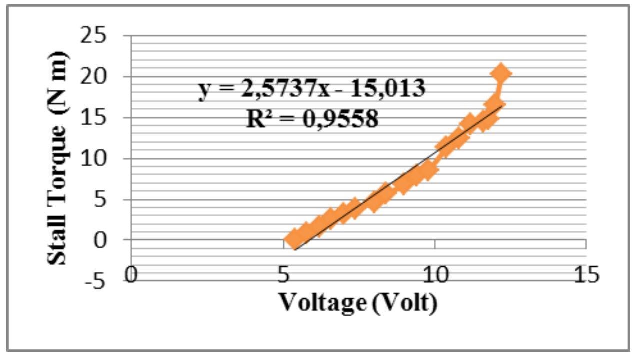

Fig. 6. Stall Torque to voltage relationship of link 2

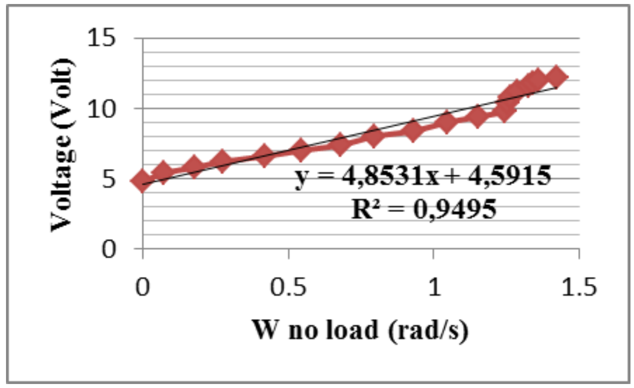

Fig. 7. Voltage to $\omega_{no-load}$ relationship of link 2

V. Result and Discussion

The last stage was to enter the PID values from the simulation results into an arduino controller with a set point in the form of data from the movement of physiotherapy. Then performance of the system in link 1 and link 2 was investigated.

A. Link 1

In Fig. 8, one of the implementation results of the physiotherapy data tracking in link 1 is shown. The figure expressed that the controller can track the physiotherapy speed data movement with good results. From these data, the average of error difference between PID speed result with the desired speed is 0.985 rpm.

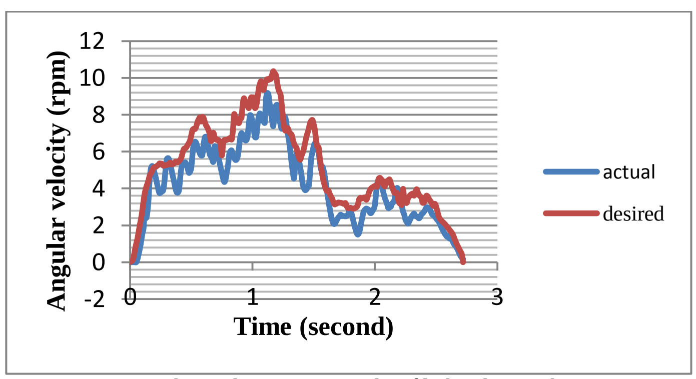

Fig. 8. The implementation results of link 1 data tracking

B. *Link 2*

In Fig. 9, one of the implementation results of the physiotherapy data tracking in link 2 is shown. The figure expressed that the controller can track the physiotherapy speed data movement with good results also. From these data, the average of error difference between PID speed result with the desired speed is 1.329 rpm.

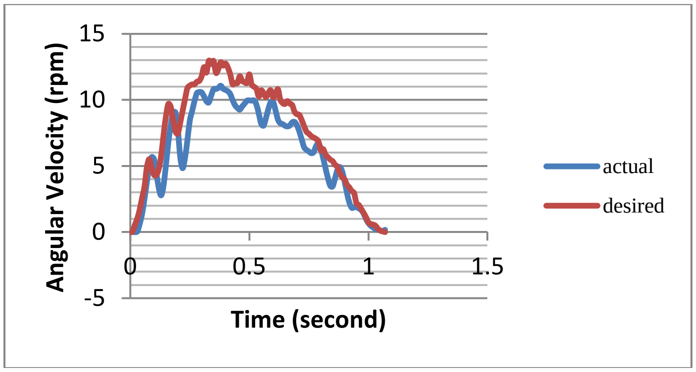

Fig. 9. The implementation results of link 2 data tracking

From Figure 8 and 9, we can see that the performance of the PID controller using PWM control input could follow and tracking the desired input signal. An error still occurs between desired signal an actual signal.

We can use the result of this research in the rehabilitation robot based on PWM control input. The proposed system can be used to realize an inexpensive rehabilitation robot that is difficult if we use a current control input.

In this paper we discussed the modeling of PID controller of rehabilitation robot with PWM input control. This means that we didn't discuss the optimal parameter for PID. It is possible to achieve better performance if we optimize the PID parameter. Based on this result, we are planning to investigate the optimal condition of PID parameter to achieve better performance of the rehabilitation robot.

VI. Conclusion

In this paper we proposed a model and design of rehabilitation robot based on PWM input control. A low cost hardware system that implemented PWM input control for the PID system was used. The system was successfully designed and manufactured. In performance testing, the robot has shown satisfactory results. This is due to the resulting error is relatively small. In the test of angular velocity, the error in both links are less than 2 rpm. It is proved that the use of PWM to control the rehabilitation robot is possible to produce robots with affordable prices, but still has a relevant function.

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