Trajectory and Current Analysis of Planar End-Effector Upper Limb Rehabilitation Device

Lim He Yue[1], Muhammad Aizzat Zakaria[2*]

[1]Innovative Manufacturing, Mechatronics, & Sports Laboratory (IMAMS), Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[2]Innovative Manufacturing, Mechatronics, & Sports Laboratory (IMAMS), Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

[*]Corresponding e-mail: maizzat@ump.edu.my

Keywords: End-effector, planar, upper-limb rehabilitation

ABSTRACT – Rehabilitation devices have become one of the more sought-after focus areas among researchers in the robotics field, where it could be used to assist patients in the process of stroke recovery. This paper illustrates the trajectory simulation and current analysis of a planar end-effector rehabilitation device for the upper limb. The rehabilitation device is of two degrees of freedom, and is used in this research due to its cost effectiveness and practicality. The trajectory tracking of the device is done via simulation in MATLAB, with a feedback control system to control the position of the end-effector. The results of the simulation suggest that the mathematical modelling of the system is able to predict the behaviour of the system, which is to be implemented in this robotic device.

1. INTRODUCTION

The number of patient population with movement disorders are on the rise in this fast-paced world, and there are many causes of the disorders, such as sports-related injuries or accidents, chronic diseases like arthritis, children with special needs, muscle sprains, stroke, and more. Physical rehabilitation is one of the main solution to these problems [1]. During the rehabilitations, physical therapists are required to repeat intensive coordinated motor movements which could be quite laborious if done for a long period of time. The process would take quite some time depending on the patients' severity in the movement disorder, and these therapies are costly to some. It is because of these reasons and the advancement in technology that people are turning to robotics as a rehabilitation alternative.

There is a wide range of research studies conducted on the devices that could assist physical rehabilitation [1], [2], [3]. The robotic devices which are technically advanced are those with the ability to perform repetitive tasks on patients, and are currently being developed. Upper limb rehabilitation alone has garnered much attention in the studies that are conducted on them and the solutions provided. Many of these devices of clinical setting are targeted at different parts of the upper limb and are tailored for different patients.

According to a survey done by Paweł Maciejasz and the team [4], the efficiency of the upper limb rehabilitation devices has room for improvement, and the cost reduction for home-based therapy and assistance are still possible. To minimize cost for rehabilitation robots in this project, the end-effector planar device could be taken as an advantage. Previous similar works have been done such as ARM Guide [5], MEMOS [6], and ARC-MIME [7], where they used planar end-effector robotic de-vices to save up on cost yet could help stroke patients in the rehabilitation process. A feedback control system is also incorporated to better control the trajectory of the device, similar to what was done in PLEMO [8].

This project aims to provide a study on an effective upper limb rehabilitation device which could be built with a minimal budget so that robotic therapy could be more accessible to patients with movement disorder.

2. METHODOLOGY

The project is carried out using MATLAB to simulate how the system would work. The trajectory of the device is then studied by controlling it using different feedback control systems: Proportional, Integral, Derivative (PID), and the current through the device is analysed.

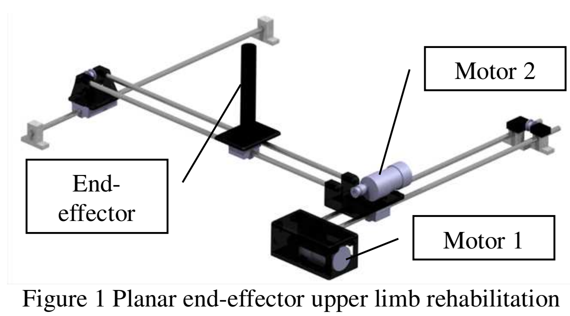


Figure 1 Planar end-effector upper limb rehabilitation device studied in this research

2.1 Motor Modelling

Two DC geared motors are used in this system to drive the end-effector. The state-space modelling of the motor is derived from two equations, a DC motor dynamics equation (1), and the system equation when load is being driven by the motor (2). From these equations, the output of the motor angle will be known given the values of different parameters.

$$\frac{d\omega}{dt} = \frac{K\varphi i}{J} - \frac{B\omega}{J} - \frac{T_L}{J} \quad (1)$$

$$\frac{di_a}{dt} = \frac{V}{L_a} - \frac{i_a R_a}{L_a} - \frac{K\omega}{L_a} \quad (2)$$

The purpose of these two equations is to simulate the model of a DC geared motor in MATLAB Simulink so that we can predict the behavior of the end-effector with the PID feedback control given the desired input of the system. ω represents the an-gular speed of the motor, $K\varphi$ refers to the E.M.F. constant, B is the viscous friction, i is the supplied current into the motor, V is the voltage supplied, R_a represents the resistance in the windings, K is the motor constant, while J is the moment of inertia of the load, and finally L_a is the inductance in the motor windings. These parameters are determined beforehand according to the datasheet of the motors, and then substituted in the MATLAB simulated model for validation. We can observe from equations (1) and (2) that the load torque, T_L influences the speed of the motor, ω. There are other factors which could influence the motor speed can also be found in the equations but the focus is on the load torque, which signifies the force exerted by the patient in the actual device.

After the system of the motors are derived, the system is modelled in Simulink with the PID feedback control system incorporated. The block diagram of the system is shown in Figure 2.

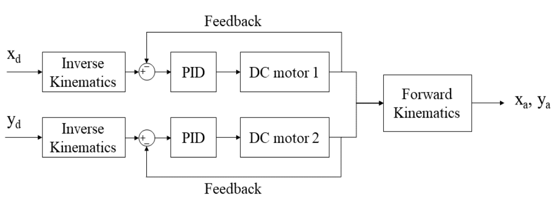


Figure 2 Feedback control block diagram

3. RESULTS AND DISCUSSION

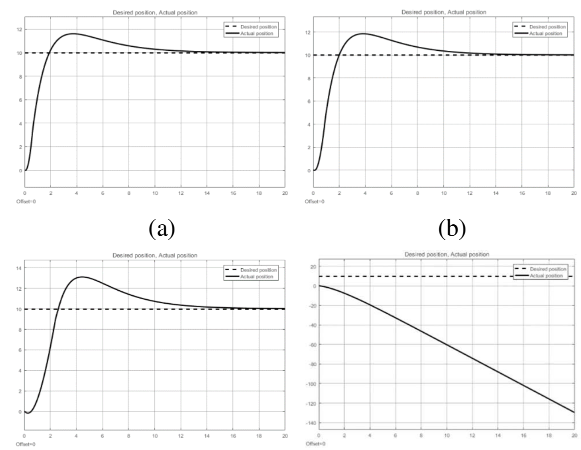
The variable in this experiment is the load torque, which represents the force exerted by the patients at the end effector. However, both models of DC motor are tested, and the desired distance is set at 10 cm for each motor model in this simulation.

The PID values are tuned manually using the intuitive method, because there is an external load torque given by the patient, T_L, and using auto-tuning would not achieve a desirable result. The PID values are then fixed for all the simulation of the different load torques.

The values of the load torque tested are chosen based on the force that is able to be exerted by a person, which is measured using a load sensor. A stroke patient is assumed to be unable to exert a force of more than 2.0 Nm in this study, therefore the values smaller than 2.0 Nm are plugged into the simulation.

Table 1 Simulation Parameters

Symbol	Value	Unit
d_1	10.0	cm
d_2	10.0	cm
K_P	80.0	-
K_I	20.0	-
K_D	70.0	-
J	10.0	kgm^2
B	0.01	Pa·s
L_a	10.0	H
R_a	2.00	Ω
K_φ	0.30	-



(a) (b) (c) (d)

Figure 3 (a) When load torque = 0.5 Nm, (b) When load torque = 1.0 Nm, (c) When load torque = 1.5 Nm, (d) When load torque = 2.0 Nm

The results are shown in Figure 3 above, and the percentage overshoot of each condition is measured. The dotted lines represent the desired position of 10 cm, whereas the full lines represent the actual trajectory of the end-effector in simulation. The percentage overshoot when load torque is at 0.5 Nm, (a) and 1.0 Nm, (b) is approximately 20%, while at 1.5 Nm, (c) it is 30%, and this proves that the PID values set are acceptable as the end-effector is able to reach the targeted position within 16 seconds. However, when the load torque is given to be 2.0 Nm as shown in (d), the graph shows a negative gradient because the loaded torque exceeds the maximum torque of the motors, and with that, the motors are unable to rotate in the correct rotation so the end-effector travels in the opposite direction.

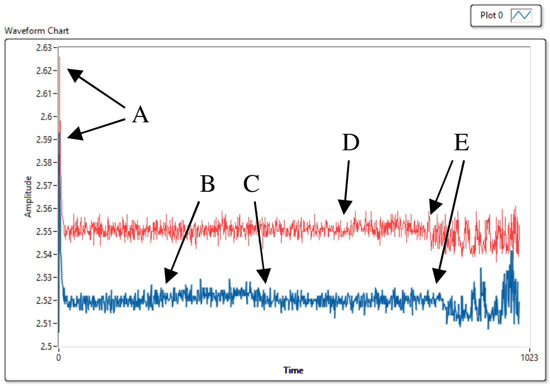


Figure 4 Feedback control block diagram

In Figure 4, the current sensor readings are shown when the end-effector traverses from the origin (0,0) to the desired end-position (7,7). The plot with higher current value represents the current value through Motor 1, while the other plot represents the current through Motor 2.

Just when the motor was started, it can be observed that there is a huge increase of current as pointed out at "A". This spike of current is due to the inertia of the system which requires a higher starting torque by the motors. Due to this, the current demand is much higher in order to overcome the inertia, then the current drops back to its constant value. Motor 1 has a higher current value due to the design of the device, it is required to carry a higher load compared to Motor 2. When the plots have a sudden high fluctuation as pointed out by "E", it signifies that the end-effector has already reached the desired end-position and has stopped. These fluctuations in current readings are known as current ripple. This phenomenon occurs when armature current is commutated and during that time. the ripples are generated by the motor inductance components in the stator windings and back-EMF of the motor [9].

Observing the plot in Figure 4 at points "B" and "D", the slight increase in current in the waveform shows that the beginning of the opposing force given to the motor causes a slight increase in. At "D", the opposing force is exerted until the end-effector comes to a stop. Therefore, the slight increase in current on this plot progresses until the bigger ripples at the end which signify the end-effector has come to a stop at the desired end-position. Whereas at "B", the current increases slightly and then drops back to its constant value at "C", because the opposing force applied on this motor was between the period of "B" and "C". In these cases, the change in current is very slight, but still observable.

4. CONCLUSION

Through this research, it is shown that PID is able to control the position of the end-effector of this rehabilitation device, but only if the load torque is within a limited range. Therefore, it is recommended to consider the dynamics the system as well, to better predict the torque required by the system and to use active force control to eliminate the disturbances from the system. In the current analysis, it is proven that the change in current is able to be detected with the aid of current sensors, so it may be a good feature to be added in a rehabilitation device to observe the improvements and recovery of a stroke patient undergoing rehabilitation.

ACKNOWLEDGEMENT

Authors are grateful to Universiti Malaysia Pahang for the financial support through grant number: RDU170371.

REFERENCES

[1] T. Proietti, V. Crocher, A. Roby-Brami, and N. Jarrasse, "Upper-limb robotic exoskeletons for neurorehabilitation: A review on control strategies," *IEEE Reviews in Biomedical Engineering*, vol. 9. pp. 4–14, 2016.

[2] R. Bertani, C. Melegari, M. C. De Cola, A. Bramanti, P. Bramanti, and R. S. Calabrò, "Effects of robot-assisted upper limb rehabilitation in stroke patients: a systematic review with meta-analysis," *Neurol. Sci.*, vol. 38, no. 9, pp. 1561–1569, 2017.

[3] R. C. V. Loureiro, W. S. Harwin, K. Nagai, and M. Johnson, "Advances in upper limb stroke rehabilitation: A technology push," *Medical and Biological Engineering and Computing*, vol. 49, no. 10. pp. 1103–1118, 2011.

[4] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, p. 3, 2014.

[5] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide.," *J. Rehabil. Res. Dev.*, vol. 37, no. 6, pp. 653–662, 2000.

[6] S. Micera *et al.*, "A simple robotic system for neurorehabilitation," *Auton. Robots*, vol. 19, no. 3, pp. 271–284, 2005.

[7] R. Colombo *et al.*, "Robotic techniques for upper limb evaluation and rehabilitation of stroke patients," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 311–324, 2005.

[8] T. Kikuchi, X. Hu, K. Fukushima, K. Oda, J. Furusho, and A. Irioue, "Quasi-3-DOF rehabilitation system for upper limbs: Its force-feedback mechanism and software for rehabilitation," in *2007 IEEE 10th International Conference on Rehabilitation Robotics, ICORR'07*, 2007, pp. 24–27.

[9] T.-S. K. T.-S. Kim, S.-C. A. S.-C. Ahn, and D.-S. H. D.-S. Hyun, "A new current control algorithm for torque ripple reduction of BLDC\nmotors," *IECON'01. 27th Annu. Conf. IEEE Ind. Electron. Soc. (Cat. No.37243)*, vol. 2, no. C, pp. 1521–1526, 2001.