MODEL IDENTIFICATION AND CONTROL OF AUTOMATIC FINGER EXTENSOR FOR HAND REHABILITATION

Nik Muhamad Ariff Kamarudin, Norsinnira Zainul Azlan*, Ifrah Shahdad, Osamah Ebrahim Mohammed Shweesh, Zabina Tasneem

Department of Mechatronics,
Faculty of Engineering,
International Islamic University Malaysia

nikariff95@gmail.com, sinnira@iium.edu.my, ishahdad3@gmail.com, osamah.2018.1996@gmail.com, zabinatasneem@gmail.com

Article history

Received: 10 May 2024

Received in revised form: 25 June 2024

Accepted: 27 June 2024

Published online: 30 June 2024

*Corresponding author: sinnira@iium.edu.my

ABSTRACT

The neurological injury in stroke patients affects the hand sensorimotor function such that the muscle weakens for voluntary movements especially in the finger extensor muscles. This condition leads to difficulty in the opening and closing of the hands. For some patients, they suffer from clenched fist or in other words, their fingers remain flexed under normal condition. This paper presents the modeling and control of an automatic finger extensor based on iris mechanism for rehabilitation therapy. The objective of this study is to determine the transfer function of the automatic finger extensor machine and to control the position of the combination of the machine's poles to achieve the desired opening size so that the patient's fingers can be extended to the required diameter repetitively in the rehabilitation treatment. The method involves a simple and fast approach of adopting the second order transfer function in the z domain and the implementation of Proportional Integral Derivative (PID) controller to control its motor and eventually its poles movement. The effect of the force from the human hand grasping the poles during the exercise is considered as a disturbance. The System Identification and PID Tuner toolboxes in MATLAB environment are utilized to obtain the coefficients of the transfer function and the PID controller gains. The results show a good fit of 72.94 % has been achieved for the system identification. From the hardware experimental test, it can be seen that the system meets the design requirement under the PID controller with steady state errors of 1.7 % and 4 % for the conditions with and without the human grasping force (disturbance) respectively. This means that the automatic finger extensor machine has successfully extended the normally flexed human fingers to the desired diameter under the controller.

***Keywords**: Clenched Fist, Finger Extensor, IRIS Mechanism, Model Identification, Proportional, Integral, Derivative (PID) Control, Rehabilitation Devices*

1.0 INTRODUCTION

Stroke is the leading cause of neurological disabilities in the world. Many stroke survivors suffer from the functional loss of mobility which is often accompanied by muscle weakness, impairments in motor coordination and sensory perceptions of the affected parts. This leaves the post-stroke patients to deal with life-long disabilities in performing activities of daily living, including reaching, grasping and object manipulation [1]. The patients undergo the conventional physical rehabilitation to overcome the effects of these impairments and improve the quality of their life. However, conventional rehabilitation treatments have the drawbacks of being immensely labour intensive and require weeks and in some cases months of one-on-one therapy sessions. This proves to be burdensome for the patients, caregivers, therapists and the healthcare systems. The conventional therapy is also highly monotonous and very often the patients lose their motivation to complete the treatment [2].

In the last decades, robot-assisted rehabilitation [3]-[6] has gained popularity as a mean of restoration of hand functions after neurological injuries due to the ability of the robots to provide precisely controlled repetitive movements coupled with assistive or resistive forces. In some robots, they provide a better engagement of the patient through immersive virtual environments, providing an additional motivation. In view of these advantages, robot-aided therapy has evolved with the development of a number of devices, especially for shoulder and elbow rehabilitation [7]. However, the efforts towards the design and development of robotic devices for the training of distal parts of the upper-limb such as wrist and fingers are rather recent [8]. This is attributed to the versatility of the hand function and the wide spectrum of post-stroke impairments which render the development of hand rehabilitation devices [7].

There are 165 devices has been identified in [9] for the restoration of hand function in post-stroke patients [9]. Considering, the design principle and the number of joints of the upper-limb the device can actuate, hand rehabilitation devices are characterized [7] as (i) powered hand exoskeletons, (ii) end-effector based devices, and (iii) entire upper-limb solutions. Among the end-effector hand rehabilitation robots, the Rutger's Master II by [10] enables the extension and flexion of four fingers. However, the robot has a small workspace and is difficult to put on by patients owing to slippage [11]. The HapticKnob [12], the ReHaptic Knob [13] and the Enable Hand are two degree of freedom (DOF) devices training for grasping and forearm pronation/supination. Clinical tests carried out with the HapticKnob have revealed significant improvements in the distal and proximal subparts of the Fugl-Meyer motor assessment in chronic post-stroke patients [7]. Yap et al. [14] has designed a flexible rehabilitation glove which is pneumatically actuated by an airbag on the back of each finger, which is driven to stretch the finger [14]. The main purpose of the hand rehabilitation is to help stroke and hemiplegic patients to stretch their hands in restoring their muscles and prevent spasticity. The device is suitable for the rehabilitation of patients with severe hemiplegia, but the pneumatic hand is single-functional, enabling only hand extension. [14].

Previously an automatic finger extensor machine based on the iris mechanism has been developed in Wahyudi Intelligent Systems Engineering (WISE) laboratory, International Islamic University Malaysia (IIUM) [5], [15]. The machine's function is to provide a robotic rehabilitation therapy to the patient's fingers by extending their clenched fist or normally flexed fingers repetitively through the opening and closing of the machine's combined vertical poles, that is actuated by a direct current (DC) motor. The machine consists of four layers which are the fixed hollow plate in the first layer, six pieces of blades equipped with vertical poles in the second layer, another plate that is connected to the DC motor through a sprocket and a chain in the third layer, and finally one more plate that holds the all the layers together in the fourth layer [5], [15]. Even though the prototype has been fully developed, a simple and fast method of modeling and controlling the mechanism has not been fully investigated yet. Since the automatic finger extensor machine contains several layers and various elements, the derivation of its mathematical modeling may be tedious and complicated. The movement of its poles combination also needs to be controlled under a specific control law so that it can extend the patients' fingers fully to the desired size and satisfies the rehabilitation treatment requirement.

This paper presents a simple approach of modeling and controlling the automatic finger extensor for rehabilitation therapy based on iris mechanism. The contribution of this paper is in determining the dynamic model of the automatic finger extensor using a second order transfer function in the z domain and investigating its control system performance under Proportional Integral Derivative (PID) controller, considering the effect of the grasping force from the user during the rehabilitation exercise. The control objective is to control the angular position of its DC motor rotation and finally the movements of the poles combination in providing the desired finger extension in the rehabilitation therapy. The System Identification and PID Tuner toolboxes in MATLAB environment are utilized to obtain the modeling coefficients and the gains of PID controller parameters. The effect of the force from the human hand grasping the poles during the exercise is considered as a disturbance in the controller implementation.

The rest of the paper is organized as follows. The methodology implemented in determining the transfer function and controlling the automatic finger extensor based on iris mechanism, including the system description, structure of the mathematical model chosen and PID controller are described in Section 2. Section 3 presents the experimental set up for the data acquisition, transfer function determination, controller gain tuning and verification of the outcomes. The results are provided and discussed extensively in Section 4. Finally, the last section draws the conclusion of this study and provides the recommendation for the future work.

2.0 METHODOLOGY

2.1 System Description

The develop finger extensor prototype for hand rehabilitation is shown as in Figures 1 and 2. The design is adopted from the iris mechanism that opens or increases in its diameter as one of its layers is rotated. Iris mechanism is widely used in camera shutters, food production, and chemicals, pharmaceuticals, minerals, and plastics materials manufacturing. The mechanism also finds numerous applications in wastewater treatment and management plants, and dense materials flow control [16].

The proposed automatic finger extensor for hand rehabilitation is made of four layers with vertical poles. The first layer is a fixed hollow plate with multiple straight sliders for blades to slide on as the mechanism is turned to open or close. On top of it are a set of six blades with isosceles triangular shape and equipped with vertical poles that travel along the sliders on the first layer. The patients hold the combination of these poles as shown in Figure 3, as it expands or shrinks while the machine extends their flexed finger joints during the rehabilitation therapy. The third layer of the mechanism is attached to the sprocket that is engaged to a direct current (DC) motor by a chain. The fourth layer of the iris mechanism holds all the four layers together using nuts and bolts. The size of the inner and outer diameters of the fourth layer are same as the first layer. The complete information on the construction of the automatic finger extensor machine based on iris mechanism can be found in [15].

The automatic finger extensor machine is powered by a 5 V DC voltage supply which is provided through the micro-controller board. A DC motor acts as the actuator for the 1-DOF automatic finger extensor mechanism. Arduino Mega 2560 microcontroller board is utilized in collecting the sensors reading and providing instructions to move the actuator. An encoder is attached to the driven sprocket and third layer of the iris mechanism to measure its angular displacement and a torque sensor is used to measure the force exerted by the patient (environment).

During the rehabilitation therapy, the patients encircle their clenched fist or normally flexed fingers around the combination of the poles as in Figure 3. As the motor rotates, the driving sprocket attached to it will turn the larger driven sprocket through the chain. The driven sprocket will in turn rotate the third layer of the mechanism and force the blades to slide along the sliders in the first layer. This will cause the combination of the poles to imitate the opening and closing movements, thus will extend the patients' fingers and then allow them to flex again. This process repeats until the end of the rehabilitation therapy.

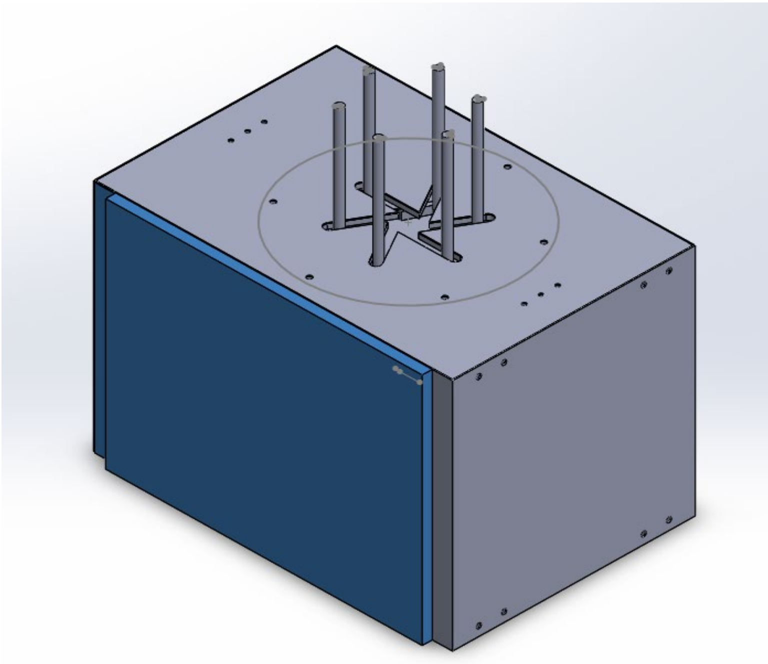

Figure 1. Automatic finger extensor machine based on iris mechanism with a casing.

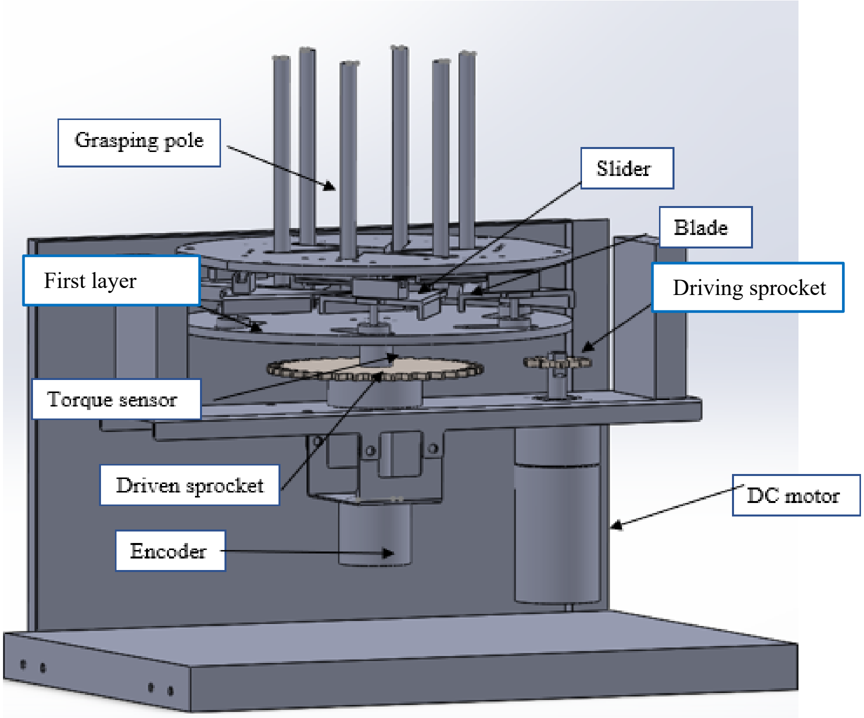

Figure 2. Inner part of the automatic finger extensor machine based on iris mechanism.

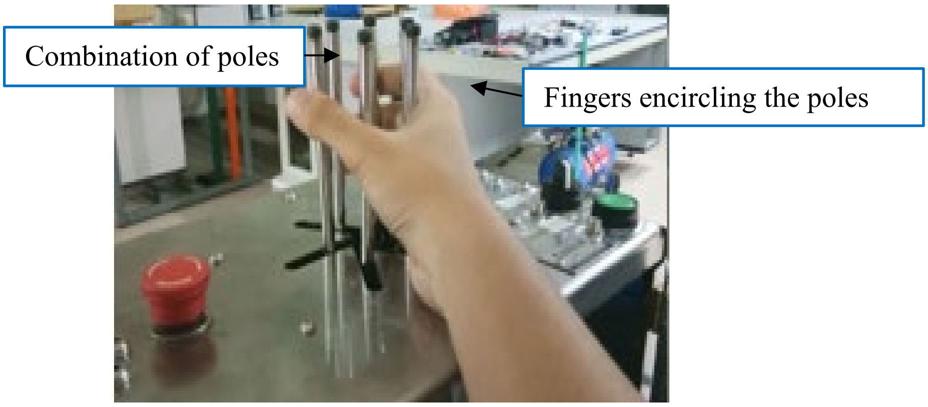

Figure 3. Human hand encircling the combination of the vertical poles of the automatic finger extensor machine based on iris mechanism.

2.2 Structure of the Mathematical Model

The input and output data of the system are captured to determine the transfer function of the physical hardware. The system identification is performed using System Identification Toolbox in MATLAB. The input and output data need to be varied and rich so that the obtained coefficients will lead to reliable and good responses. The external mode of the Arduino Mega 2560 microcontroller used in the hardware requires a discrete block diagram to run the program. After several trials, a second order transfer function in the z domain has been chosen to represent the dynamics of the system where,

$$G(z) = \frac{a_2 z^2 + a_1 z^1 + a_0}{b_2 z^2 + b_1 z^1 + b_0} \quad (1)$$

$G(z)$ is the open loop transfer function of the system, a_2, a_1 and a_0 are the coefficients of z^2, z^1 and z^0 respectively for the numerator and b_2, b_1 and b_0 are the coefficients of z^2, z^1 and z^0 respectively for the denominator of the identified transfer function.

2.3 PID Controller

The control objective in this work is to control the angular position of the motor that will in turn move the third layer of the iris mechanism and leads the blades to slide along the sliders situated on the first layer of the iris mechanism. This will cause the vertical poles on the blades to move together and their combination will make an opening or closing movements, that will extend the clenched fist or normally flexed patients' fingers and then allowing them to flex again repeatedly. The controller design specifications include a steady state error less than 5 %, percentage overshoot less than 30 % and maximum setting time of 3s for a sufficient operation of the automatic finger extensor.

The PID Tuner Toolbox in MATLAB is used for the controller implementation of the hardware. The transfer function obtained from the System Identification toolbox is imported to the Tuner Toolbox, where the PID controller gains are auto-tuned so that the best combination of the controller gains can be obtained. There are several options for the controller implementation which are Proportional (P), Proportional Integral (PI), Proportional Integral Derivative (PID), and Proportional Integral Derivative with Filter (PIDF) options. PIDF has been chosen in this study due to its efficient response and ability to achieve the steady state in the shortest possible time compared to P, PI and PID. Unlike PID, PIDF has an additional coefficient *N*, the first order filter coefficient for the derivative term as is stated by the equation

$$C(z) = K_p + T_s.\frac{1}{z-1}.K_i + K_d.\frac{N}{1 + N.T_s.\frac{1}{z-1}} \quad (2)$$

in the *z* domain. $C(z)$ s the controller transfer function, K_p, K_i and K_d are the proportional, integral and derivative gains of the controller respectively, and T_s is the sampling time.

In this study, the effect of the force from the normally flexed patients' hand is considered as a disturbance. In the beginning, the closed loop control system is implemented without the human hand encircling the poles of the automatic finger extensor machine to observe its feasibility in performing the hand opening and closing movements as specified in the design requirement. Then the effect of the force exerted by the normally flexed patients' fingers or clenched fist is considered by adding a disturbance block that represents the force from the patients' fingers grasping the poles as shown in Figure 4.

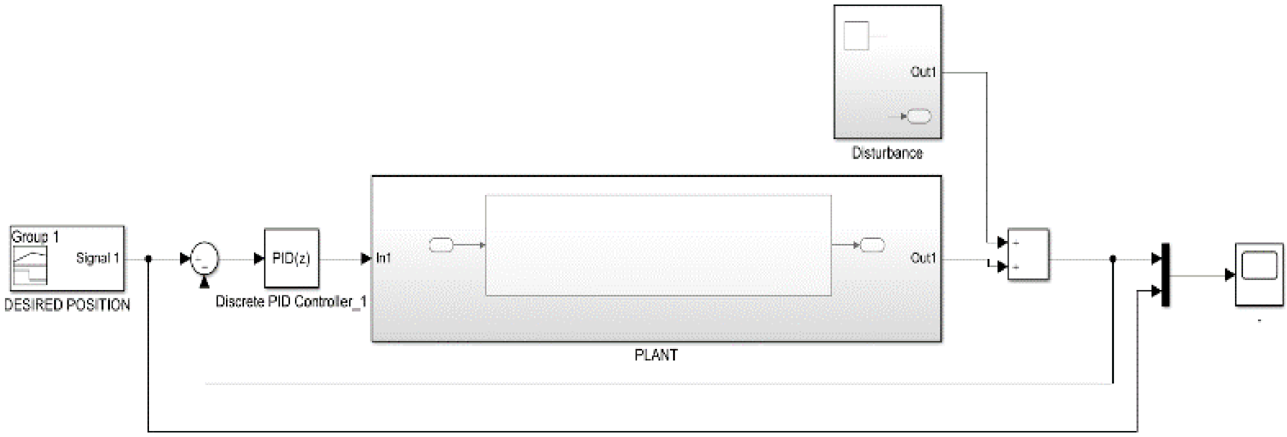

Figure 4. Closed loop block diagram of the proposed automatic finger extensor machine based on iris mechanism with disturbance (force exerted by the clenched fist or normally flexed finger)

3.0 EXPERIMENTAL SETUP

The experimental setup for the system identification and position control of the automatic finger extensor for hand rehabilitation system is shown in Figure 5. The encoder and motor of the automatic finger extensor prototype are connected to the Arduino microcontroller board which is then connected to the laptop through a USB cable for the Arduino programming and MATLAB toolboxes utilization.

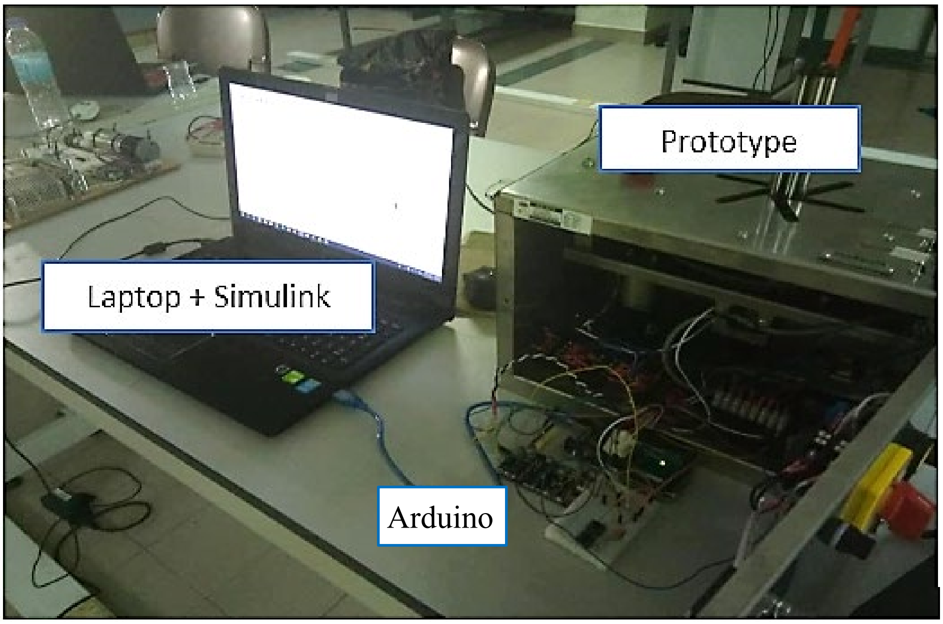

Figure 5. Experimental set up for the data acquisition and controller implementation

4.0 RESULTS AND DISCUSSIONS

4.1 System Identification

The input, which is the voltage supplied to the automatic finger extensor machine, and the output, which is the position response of the motor rotor measured by the encoder have been recorded from the hardware experimental test. The data collected have been imported into the System Identification Toolbox in MATLAB with a sampling time of 0.02 seconds as shown in Figure 6. The model structure has been chosen as a second order transfer function in the discrete time domain. The resulting model identified has been obtained as

$$G(z) = \frac{-0.000183050480299350z^2}{z^2 - 1.994157495183289z + 0.994584449250213} \quad (3)$$

The resulted transfer function has been tested using the same input to evaluate its effectiveness in capturing the dynamics of the actual system, where it should approximate a good fit for the original output. Figure 7 shows the comparison between the measured and the simulated responses from the identified transfer function governed by Equation (3). From the figure, it can be seen that the transfer function produces a good fit of 72.94 %. The cross-correlation plot between the input and the residuals is shown in Figure 8. This plot verifies that a good transfer function has been generated in this case, where the resulting cross-correlation function lies between the confidence region indicated by the dashed lines. Therefore, it can be said that that the residuals of the models are not correlated with and independent of the past inputs, which validates the "goodness" of the model.

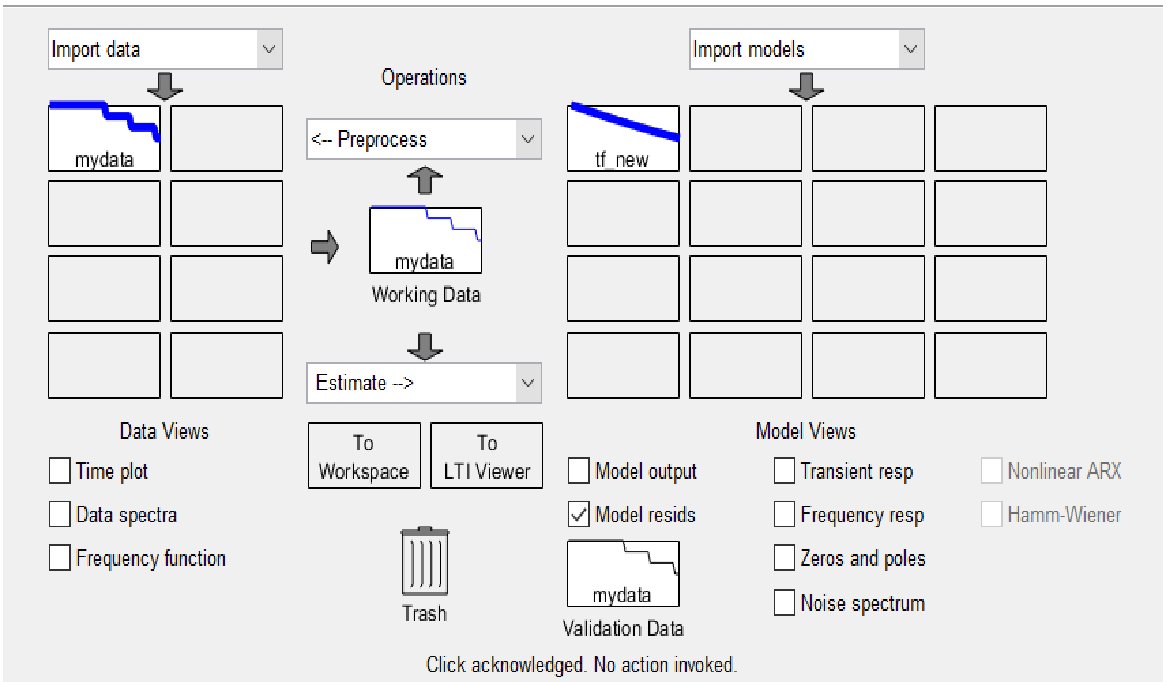

Figure 6. System Identification workspace in MATLAB

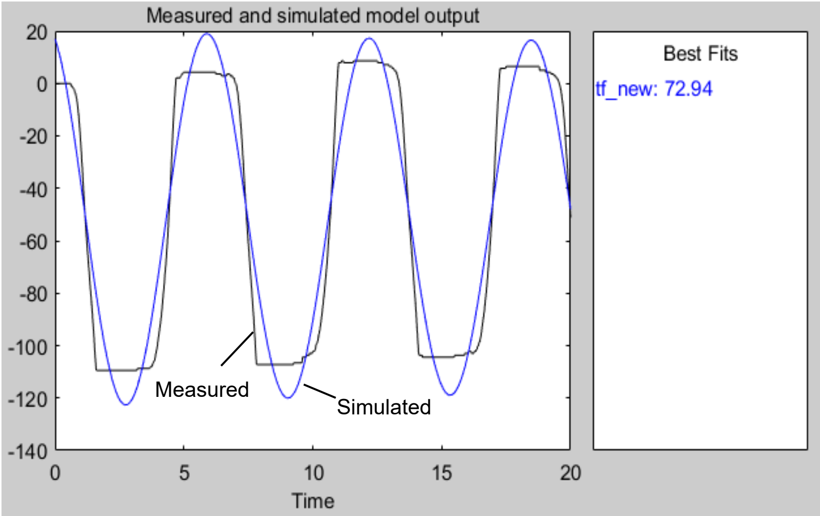

Figure 7. Measured and simulated model outputs

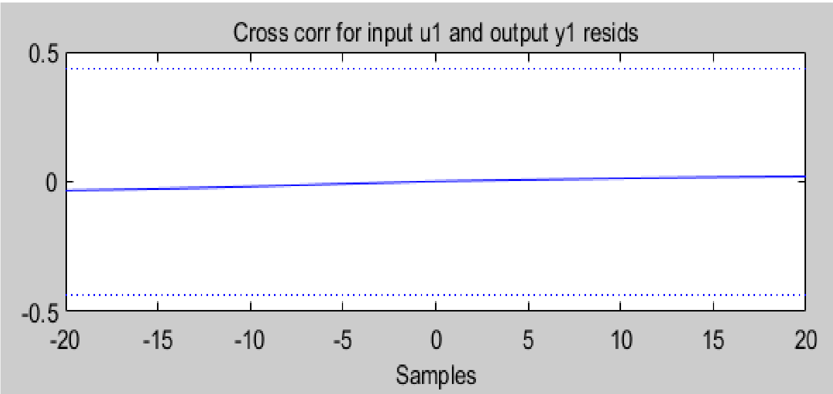

Figure 8. Cross-correlation of the input and output residue.

4.2 Closed Loop Control without Disturbance

The transfer function of the automatic finger extensor machine that has been obtained from the System Identification toolbox in Equation (3) has been imported to the Tuner Toolbox to tune the PID controller gains in controlling the position of the machine's motor and the poles combination as it extends the user's fingers. At this stage of the experiment, the patient's fingers are not placed at the combined poles yet to observe the system response without any disturbance. Therefore, the tuning has been done without taking into consideration the effect of the human hand encircling the combined poles during the rehabilitation therapy. Using MATLAB toolbox, the gains for the controller K_p, K_i, K_d and N in Equation (2) have been obtained as -5270.4155, -2629.1315, -15.6965 and 0.011661 respectively.

The step response of the closed loop control of the automatic finger extensor system using the identified transfer function in Equation (3) is illustrated as in Figure 9. From the figure, it can be observed that the rise time of the output is 0.0177 s, percentage overshoot obtained is 22.3 % the settling time is 0.241 s and the steady state error is 0 %. The performance of the automatic finger extensor under the PID control is acceptable and fulfils the design specifications.

An experiment has been conducted on the actual hardware or prototype of the automatic finger extensor machine with a series of three pulses input signal with a duration of 3 seconds and 1 second interval. The comparison of desired output, actual system performance and simulated response using the identified transfer function is shown in Figure 10. The result shows that the actual response from the hardware prototype follows the desired trajectory with a settling time of 1 s and steady state error of 4 %. The simulated results from the obtained transfer function also exhibits a similar pattern of movement as the actual motion of the hardware and tracks the desired output. These results are acceptable and fulfil the design requirements.

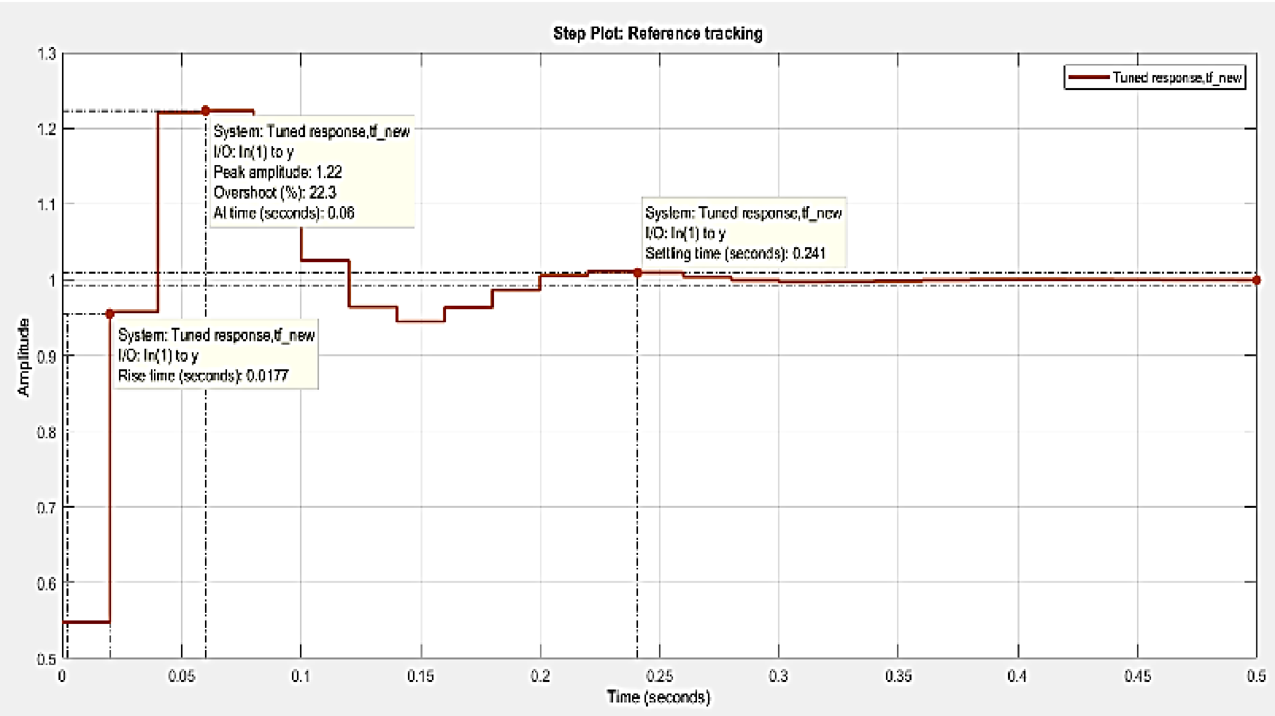

Figure 9. Step response of the automatic finger extensor using the identified transfer function without disturbance (no human hand is grasping the poles of the automatic finger extensor).

PERINTIS eJournal, 2024, Vol. 14, No. 1, pp. 8-24

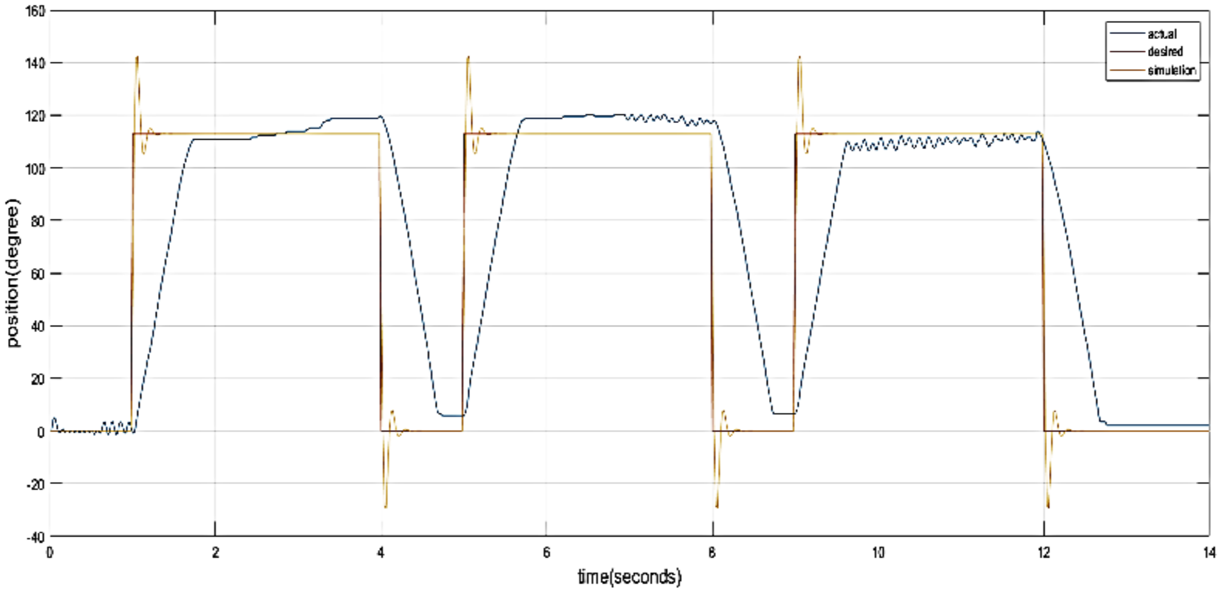

Figure 10. Comparison of the actual and simulation results of the position control without disturbance (no human hand is grasping the poles of the automatic finger extensor).

4.3 Closed Loop Control with Disturbance

In this experiment, the human hand is placed encircling the poles of the automatic finger extensor machine as shown in Figure 3. The machine provides repeated extension movements of the human fingers during the rehabilitation therapy. As mentioned previously, the clenched fist or normally flexed human hand that is to be extended as the machine opens and closes its pole combination is considered as a disturbance. At this stage of study, only healthy human hand is involved in the test to simplify the experiment procedure and observe the machine's feasibility and outcome in extending the human fingers. The force exerted by the human hand on the poles is recorded using the torque sensor as depicted in Figure 11. The inconsistencies or fluctuations of the grasping force as shown in the figure is due to the opening and closing of the mechanism that leads to "no-grasping" points in between the sequence of the poles opening and closing.

The actual prototype and simulated responses of the system under the same PID controller and gains as in the previous experiment can be observed in Figure 12. It can be seen that that the steady state error is 14 % and 15 % for the actual and simulated response respectively. This means that the machine does not fully open the poles combination as desired and the extension movement of the human finger is not fully realized. In other words, the machine does not open or extend the patient's hand to the desired position and therefore, it does not meet the main objective of the design requirement.

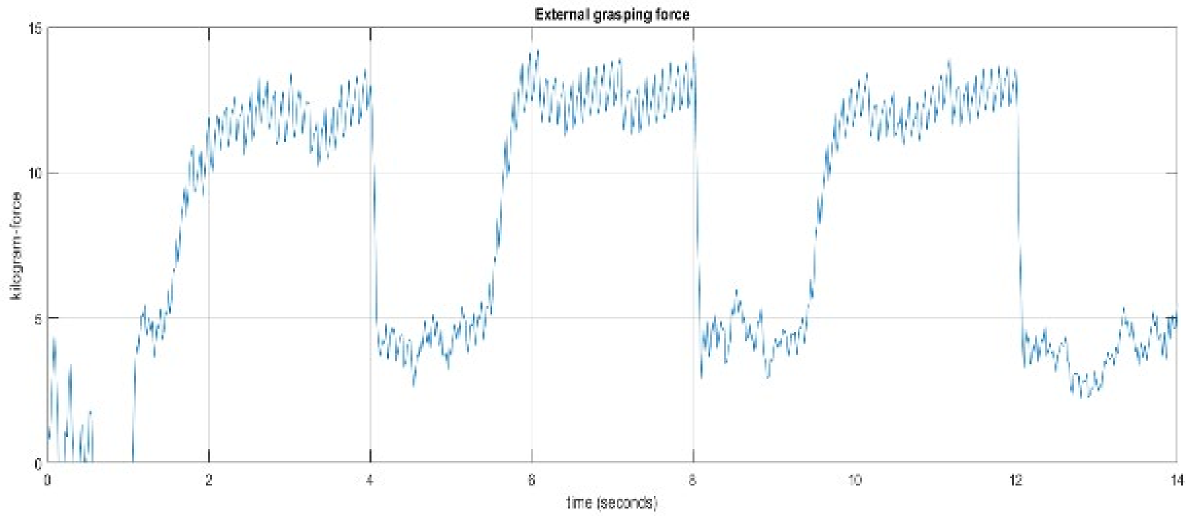

Figure 11. Measured external grasping force from human hand during the opening and closing of the combined poles.

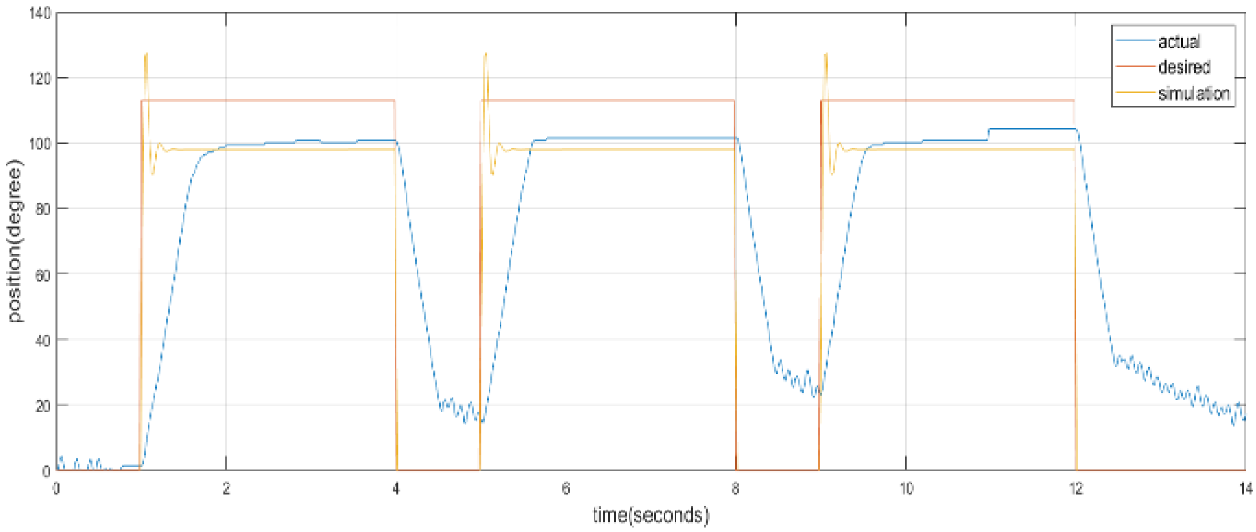

Figure 12. Comparison of the actual and simulation results of the position control with disturbance (human hand is grasping the poles of the automatic finger extensor).

The gains of the PID controller have been adjusted to overcome this problem using the PID Tuner toolbox in MATLAB programming. At this time, the new tuning has been done considering the force from the human hand grasping the poles of the automatic finger extensor machine. After several trials, the new values of the controller gains K_p, K_i, K_d and N in Equation (2) have been obtained as -5718.8743, -2859.4052, 0.86709 and 0.010152 respectively.

The step response of the simulated closed loop control of the automatic finger extensor using the identified transfer function and the adjusted PID control gains has been obtained as in Figure 13. Referring to the figure, the rise time, percentage overshoot, settling time and steady state error of the closed loop control system are 0.0159 s, 25.7 %, 0.233 s and 1 % respectively. From this result, it can be seen that the performance of the system has improved compared to the one using the previous PID gains. The automatic finger extensor machine is able to fully extend the clenched fist or normally flexed human hand as desired and provide the required rehabilitation therapy whilst meeting the design requirements.

Similarly, the experiment has been repeated on the actual hardware or the prototype of the automatic finger extensor machine with the similar pulse input. The comparison of the actual system performance, simulated response using the identified transfer function and the desired output is shown in Figure 14. The result shows an improved response under the new PID controller gains compared to the previous ones shown in Figure 12. The resulting steady state error of the actual and simulated output are 1.7 % and 0 % respectively, which means that the machine has successfully opened its poles combination to the desired diameter. The percentage overshoot and settling time in the actual response are 1.7 % and 1.3 s respectively also shows that the system meets the controller design requirement. The performance of the simulated system also shows a better result under the readjusted PID gains, where the simulated system output tracks the desired output with zero steady state error and percentage overshoot of 21 % and 0.3 s settling time.

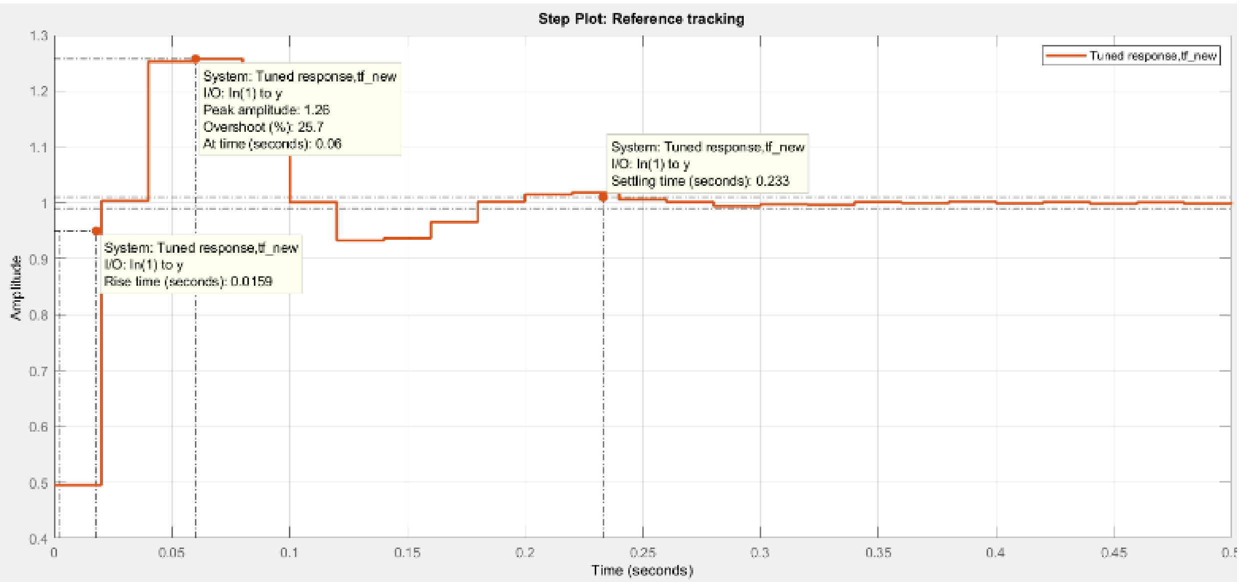

Figure 13. Step response of the automatic finger extensor using the identified transfer function with disturbance (human hand is grasping the poles of the automatic finger extensor).

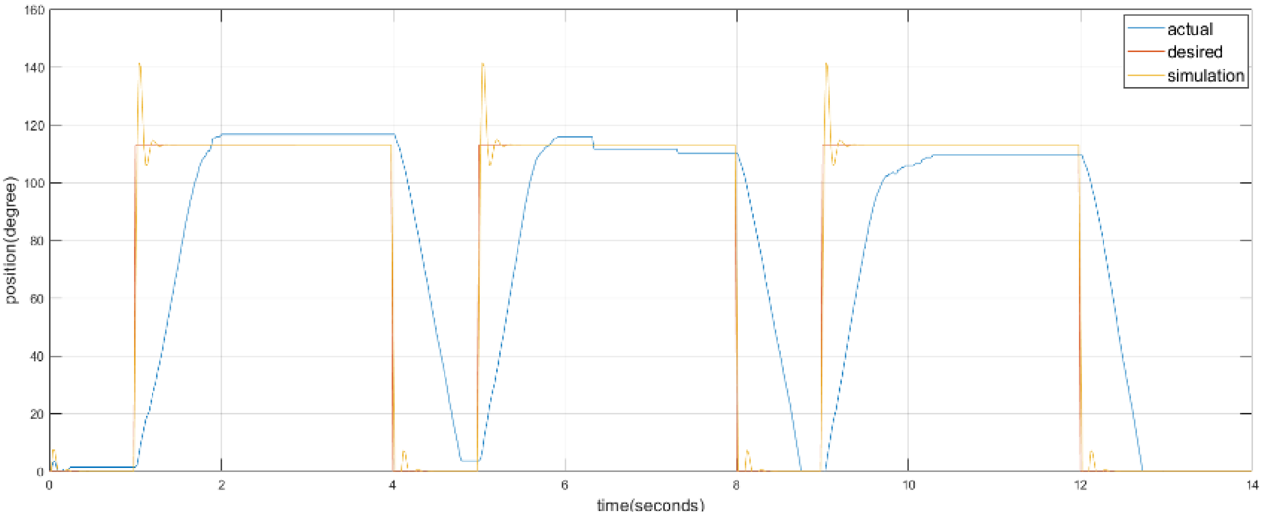

Figure 14. Step response of the automatic finger extensor using the identified transfer function with disturbance (human hand is grasping the combination of poles of the automatic finger extensor).

4.4 Discussion

The automatic finger extensor based on iris mechanism consists of several layers and combination of multiples parts that leads to complex structure. This paper presents a simple approach of modeling and control of an automatic finger extensor machine. The mathematical model of the machine has been obtained using the transfer function structure of a linear system by implementing the System Identification toolbox in MATLAB environment. The results is satisfactory with a good fit of 72.94 %. A more accurate dynamic model of the automatic finger extensor may be obtained by trial and error method utilizing other model structures such as state space model, polynomial model, process model and nonlinear model. Alternatively, the mathematical model of the system can also be constructed analytically instead of applying trial and error method, using the Lagrange or Newton-Euler equation and considering the friction, inertia, damping and stiffness factors of the elements in the mechanism. The implementation of the PID controller in this study also represents a simple approach to control the opening diameter of the combined poles of the machine in extending the human finger to the desired size in the rehabilitation therapy. The force exerted by the human hand while encircling the combined poles of the machine has been considered as a disturbance and the PID gain has been readjusted to meet the design requirement. The PID controller gains value and performance of the system with and without external disturbance from the human hand grasping the machine's combined poles are summarized in Tables 1 and 2. Good system performance has been achieved using this method where the system meets the required steady state error, settling time and percentage overshoot. However, a more advanced or robust controller such as adaptive controller, sliding model controller or neural network controller can be designed for the system to overcome the uncertainties in the various amount of force from the human hand encircling the machine's poles due to the different level of illness or impairment of the clenched fist or normally flexed patient's fingers to be extended. At this stage of study also, the healthy human hand is used to imitate the effect of the patients' hand for the simplicity of the experiment and observing the feasibility of the controller in providing the required fingers extending motion in the therapy. However, future study need to involve the data from real patients with various health conditions and recovery levels for a more accurate and practical implementation of the automatic finger extension machine in providing the rehabilitation therapy for the patients.

Table 1. PID controller gains for the automatic finger extensor machine.

PID gains	Without external force	With external force
K_p	-5270.4155	-5718.8743
K_i	-2629.1315	-2859.4052
K_d	-15.6965	0.86709
N	0.011661	0.010152

Table 2. Simulation results of the closed loop control of finger extensor machine based on iris mechanism.

PID gains	Without external force	With external force
Peak amplitude	1.22	1.26
Overshoot (%)	22.3	25.7
Rise time (seconds)	0.0177	0.0159
Settling time (seconds)	0.241	0.233
Steady state error (%)	0	1

5.0 CONCLUSION

This paper presents a simple approach of modeling and control of an automatic finger extensor machine based on iris mechanism using the System Identification and PID Tuner toolboxes in MATLAB environment. A second order transfer function in the z domain has been chosen as the model structure. The external force from the human hand grasping the poles of the machine has been considered as a disturbance in this study. Good results has been obtained in both the system identification and the position control of the system without and with the human finger encircling the machine's poles during the rehabilitation therapy. A good fit of 72.94 % has been achieved for the system identification of the linear transfer function of the system. The system has attained steady state errors of 4 % and 1.7 % under the PID controller for without and with the human grasping force conditions respectively. This means that the automatic finger extensor has successfully extended the normally flexed human fingers to the desired opening diameter under the controller. Future studies involves the development of the dynamic model of the automatic finger for a more accurate mathematical model the utilization of a more advanced or robust controller to overcome the uncertainties in the various amount of forces from the human hand encircling the machine's poles that is due to the different level of illness or impairment of the clenched fist. Future works also need to usage of the data from real patients with various health conditions and recovery levels for a more accurate and practical implementation of the automatic finger extensor machine.

Acknowledgement

The authors would like to thank International Islamic University Malaysia (IIUM) for providing the financial support for conducting this study under the grant number: P-RIGS18-019-0019.

REFERENCES

[1] F. Marini, C. M. Hughes, V. Squeri, L. Doglio, P. Moretti, P. Morasso, and L. Masia, “Robotic wrist training after stroke: Adaptive modulation of assistance in paediatric rehabilitation,” Robotics and Autonomous Systems, vol. 91, pp. 169-178, 2017.

[2] J. L. Patton, and F. A. Mussa-Ivaldi, “Robot-assisted adaptive training: custom force fields for teaching movement patterns,” IEEE Transactions on Biomedical Engineering, vol. 51, no. 4, pp. 636-646, 2004.

[3] Z. A. Adeola-Bello, N. Z. Azlan, and S. A. A. Hassan, “Control strategy for power assist upper limb rehabilitation robot with the therapist’s motion intention prediction,” IIUM Engineering Journal, vol. 24, no. 1, pp. 285-300, 2023.

[4] S. Y. A. Mounis, N. Z. Azlan, and Z. Hussain, “Design and control of a robotic device for upper limb rehabilitation therapy,” Journal of Engineering Science and Technology, vol. 17, no. 2, pp. 1306-1327, 2022.

[5] I. Shahdad, N. Z. Azlan, and A Jazlan, “Modelling of a 1-DOF finger extensor machine for hand rehabilitation,” IIUM Engineering Journal, vol. 22, no. 2, pp. 384-396, 2021.

[6] N. Z. Azlan, and N. S. Lukman, “Assist as needed control strategy for upper limb rehabilitation robot in eating activity,” IIUM Engineering Journal, vol. 22, no. 1, pp. 298-322, 2021.

[7] O. Lambercy, R. Ranzani, and R. Gassert, “Robot-assisted rehabilitation of hand function,” Rehabilitation Robotics, Academic Press, pp. 205-225, 2018.

[8] V. Squeri, L. Masia, P. Giannoni, G. Sandini, and P. Morasso, “Wrist rehabilitation in chronic stroke patients by means of adaptive, progressive robot-aided therapy,” IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 22, no. 2, pp. 312-325, 2013.

[9] R. A. Bos, C. J. Haarman, T. Stortelder, K. Nizamis, J. L. Herder, A. H. Stienen, and D. H. Plettenburg, “A structured overview of trends and technologies used in dynamic hand orthoses,” Journal of Neuroengineering and Rehabilitation, vol. 13, pp. 1-25, 2016.

[10] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, "The Rutgers Master II-new design force-feedback glove," IEEE/ASME Transactions on Mechatronics, vol. 7, no. 2, pp. 256-263, 2002.

[11] L. Dovat, O. Lambercy, R. Gassert, T. Maeder, T. Milner, T. C. Leong, and E. Burdet, "HandCARE: a cable-actuated rehabilitation system to train hand function after stroke," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 16, no. 6, pp. 582-591, 2008.

[12] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner, "A haptic knob for rehabilitation of hand function," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 3, pp. 356-366, 2007.

[13] J. C. Metzger, O. Lambercy, D. Chapuis, and R. Gassert, "Design and characterization of the ReHapticKnob, a robot for assessment and therapy of hand function,". Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3074-3080, 2011.

[14] H. K. Yap, J. H. Lim, J. C. H. Goh, and C. H. Yeow, "Design of a soft robotic glove for hand rehabilitation of stroke patients with clenched fist deformity using inflatable plastic actuators," Journal of Medical Devices, vol. 10, no. 4, pp. 44504, 2016.

[15] M. A. Ali, N. Z. Azlan, "Design of iris mechanism for flexion and extension training in hand rehabilitation," ARPN Journal of Engineering and Applied Sciences, vol. 11, pp. 4115-4122, 2016.

[16] STILONN Valves & Controls Pvt Ltd, "How does an iris valve work and its application", 2021. https://www.stilonn.com/blog/how-does-an-iris-valve-work-and-its-application, Last accessed 17 April 2024