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Force Control for One Degree of Freedom Haptic Device using PID Controller

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Abstract: Haptics has been used as an additional feedback to increase human experience to the environment over years and its application has been widening into education, manufacturing and medical. The most developed haptic devices are for rehabilitation purposes. The rehabilitation process usually depends on the physiotherapist. But it requires repetitive movements for long-term rehabilitation, thus haptic devices are needed. Most of the rehabilitation devices are include haptic feedback to enhance therapeutic outcome during the rehabilitation process. However, the devices typically incorporate multiple degrees of freedom (DOF), complex design, and are costly. Rehabilitation for hand movement such as grasping, squeezing, holding and pinching usually does not need an expensive and complex device. Therefore, the goal of this study is to develop a simple one DOF Haptic Device for grasping rehabilitation exercise. The performance of the haptic device is tested with different conventional controllers, such as Proportional (P) controller, Proportional-Integral (PI) controller, Proportional-Derivative (PD) controller and Proportional-Integral-Derivative (PID) controller, to obtain the best proposed controller based on the lowest value of Mean Square Error (MSE). The results show that PID Controller (MSE = 0.0028) is the most suitable for the haptic device with Proportional gain (K_p), Integral gain (K_i) and Derivative gain (K_d) are 1.3, 0.01 and 0.2 respectively. The force control algorithm can imitate the training motion of grasping movement for the patient.

Keywords: Haptic, force control, rehabilitation, stroke, controller

1. Introduction

A normal hand function incorporates several components, including dexterity, strength and range of motion (ROM) [1]. Damage to one or more of these components can lead to dysfunction of hand, limits their daily activities, participation in society and the likelihood of returning to their work [2]. Peripheral nerve injury, arthritis and stroke are one of the causes of hand function loss which due to injuries, illnesses or defects. Among those causes, stroke ranked third as the highest cause of death rate and being in top ten cause for hospitalization in Malaysia [3].

In medical term, a stroke is called as cerebrovascular accident (CVA). It occurs when blood supply to the brain is interrupted due to injury. This reduces the supply of oxygen and nutrients hence damages the brain cells [4-6]. When this happens, part of the body controlled by the damage brain cells will stops working. The severity of stroke depends on where it happens and how much the brain is affected. Minor stroke causes such arm or leg weakness. While a major stroke may lead to a paralysis or death. This disease can be faced by all ages but frequently happens to middle ages and above.

The stroke patients can enhance the relearn skill of brain by undergoing a rehabilitation program. Rehabilitation can be defined as an action to restore someone health or normal life after an addiction or illness through training and therapy [7]. The physiotherapist will monitor the progress of the patients for a certain period of time based on their condition. Rehabilitation probably does not cure but help patient with best possible long term outcome.

Finger rehabilitation concentrate on how the motor skill operates at the finger. Motor skill can be defined as a combination of series movements to produce a smooth and efficient action. It can be categorized into two types which are fine motor skill and gross motor skill [8]. Fine motor skill focused more to dexterity in the movement of small muscle in contact with movement of eye to control the fingers, thumb and hand. On the other hand, gross motor skill is more on grasping the large object. The combination of rehabilitation with specialized device would help the stroke patient to improve their motor ability of hand and fingers. Besides, the performance evaluation of the patients can be make more precisely and effectively. Hence, its presence helps physiotherapists to assess the stroke patients during their rehabilitation process [9].

Therefore, the objective of this study is to develop a one degree of freedom (DOF) Haptic Device for grasping rehabilitation exercise by using a small DC gear motor and a load cell act as force sensor together with force control algorithm. The handle of the haptic device is attached with a 5 kg load cell and geared DC motor. The device performance was analyzed with different types of conventional controllers, which are Proportional (P) controller, Proportional-Integral (PI) controller, Proportional-Derivative (PD) controller and Proportional-Integral-Derivative (PID) controller. A primary focus of the study is to propose a suitable controller for the haptic device through performance evaluation based on the lowest value of Mean Square Error (MSE) of between the desired and actual haptic forces. MSE is used to ensure the system can reach its final state quickly as well as steady state error is small.

2. The Material Method

2.1 Literature Review (Finger Rehabilitation Robot and its Controller)

Examples of research on force control, particularly for the robotic hand can be found in [10-12]. Most of these research studies aim mainly to create a biomechanically realistic human hand. Olivier Lambercy *et. al.* [13] designed ReHaptic Knob that builds on a similar end-effector approach to the Haptic Knob [14]. The robot consists of two control mechanism. The robot is controlled by PID position controller in the opening course and provides a resistive force consisting of a constant force and a damping component in the closing course.

Jun Wu *et. al.* [15] developed a pneumatic muscle-driven therapeutic device that is wearable and supports the grasping and extension of finger. A fuzzy-PID controller is used to control the trajectory tracking of this device. PR2 Humanoid Robot [16] is a wearable device that can be wears on the index finger and thumb of the user and enables them to control the robot's grip aperture with a pinching movement. A PD controller is used to drive the robot grip aperture to match the current grip aperture of the human, as measured by the motor encoder.

MIME [17] uses a PID controller to allow stroke survivors to exercise point-to-point three-dimensional (3D) movements in the real world. The subject's arm is attached to the wrist splint. The interaction force between the subject and the device is measured with a force sensor. Xikai Tu *et. al.* [18] designed RUPERT since some stroke patients have difficulty moving in one direction, thus RUPERT can help patients' movement as it comes with a unidirectional pneumatic muscle action (PMA). H. Kawasaki *et. al.* [19] produced a new hand motion assist robot for rehabilitation therapy. It is an exoskeleton based robot with 18 DOFs and has a self- motion control system that allows a patient's hand to be driven by his or her healthy hand from the opposite side.

A single DOF finger exoskeleton [20] for grasping was designed to implement admittance control. The admittance control allows the user to use force as an input and translates that force into a motion. A strain gauge load cell was installed on the index finger thimble aligned with the direction of finger flexion-extension. The calculated position values were converted to motor positions and sent to a motor using the PID controller to obtain the desired position. One Degree of Freedom Haptic Device for Hand Therapy Exercise [21] is a device that is equipped with a sensory and control device such as encoder, motor and Arduino Mega that connects with a computer.

However, all of these robotic rehabilitation systems are complex, costly and requiring technical assistance. Generally, the more complex the mechanical design, the more expensive, less safe and less number of potential users it has [22]. However, all of these studies are complex and costly, therefore, it would be beneficial if a simple device with few DOF can be designed to rehabilitate hand function as efficiently as existing complex robotic devices.

2.2 System Architecture

The overall system architecture is shown in Fig. 1. The device is powered by a 12V DC power supply. The Arduino Mega 2560 is used as the brain of the system. In Fig. 1, on the left side shows the mechanical part of the haptic device. Motor driver controls the movement of the micro metal gear motor. The motor is directly attached to the handle through a flange coupler. The load cell is attached to the handle to provide the input for force measurement. This feedback enables the motor to be controlled more precisely to obtain the desired force for the patient. While the proposed controller is shown on the right side, the computer is used to calculate the desired force based on the proposed controller. A graph is displayed on the computer screen to visualize in real-time whether the proposed controller can reach the assigned setpoint or not.
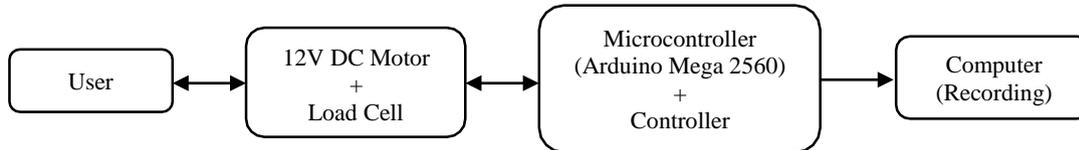

Fig. 1 - The overview of system architecture.

2.3 Block Diagram

The block diagram of this project is shown in Fig. 2 (a). The desired force is set as 0.5 N to imitate the grasping mechanism. The error obtained from desired force and actual force generate output for the controller. The output from the controller is scaled (multiplied with coefficient of 100) to match the input pulse-width modulation (PWM) for the micro metal gear motor. The final output is the value measured from the load cell. The force control is important to imitate training motion of grasping movement for patient who unable to open their hand on the early stage. This training will help to open the patient's hands according to the set force.

2.4 Programming Flowchart

The programming language for software development is in C++. Before the coding was written, the overall software flowchart was designed as shown in Fig. 2 (b). The handle stays at original position when at rest. The process starts if force is applied onto the load cell. The error obtained from the desired force and the actual force acts as the input to the controller, whose output is then multiplied to a coefficient to get the input PWM for the micro metal gear motor. If the input PWM obtained is more than 255, the handle moves forward (release) and it move backward if the input PWM is less than -255 (grasp). A limit switch is placed for safety purposes to avoid damage to the gear motor and to stop the device.
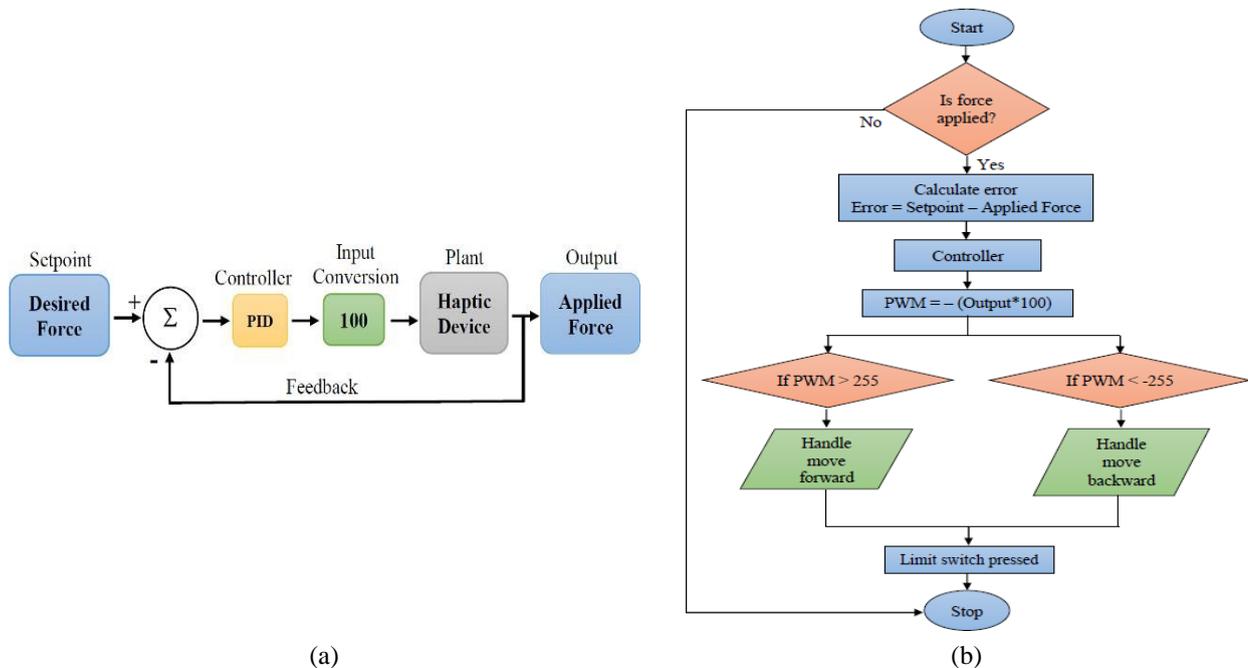

(a)

(b)

Fig. 2 - (a) The block diagram of haptic device and (b) the programming flowchart of haptic device.

2.5 Controller Methods

The haptic device is tested with four types of conventional controller which are Proportional (P) controller, Proportional-Integral (PI) controller, Proportional-Derivative (PD) controller and Proportional-Integral-Derivative (PID) controller. The haptic device with no controller is used as reference for selecting the best controller based on the lowest MSE value. Each controller was explained with the aid of block diagrams. Conventional control is used because it offers robust and reliable performance for most systems if the parameters are set or tuned to ensure a satisfactory closed-loop performance. The device is first tested without a controller and followed by four kinds of controller methods. The values of each controller constant were tuned using heuristic method.

a) *Without Controller*: As a reference, the error from the desired force and applied force is directly use as the input to the micro metal gear motor.

$$Error = Setpoint - Applied\ Force \qquad (1)$$

b) *Proportional (P) Controller*: The output for P controller is calculated as follow. The output then converted as an input to the micro metal gear motor.

$$P - Term = K_p.(t) \qquad (2)$$

where; K_p = Proportional gain and $e\ (t)$ = Error at the present time "t"

c) *Proportional-Integral (PI) Controller:* Equation 3 shows PI controller output which then converted as an input to the micro metal gear motor.

$$PI - Term = K_p . e(t) + \int_0^\tau K_i . e(t)dt \qquad (3)$$

where; K_i = Integral gain and τ = Total time of operation of the controller

d) *Proportional- Derivative (PD) Controller:* The output for PD controller is calculated using Equation 4. The output from PD controller then converted as an input to the micro metal gear motor.

$$PD - Term = K_p . e(t) + K_d . \frac{de(t)}{dt} \qquad (4)$$

where; K_d = Derivative gain

e) *Proportional-Integral-Derivative (PID) Controller*: Equation 5 shows the output of PID controller which is then converted as an input to the micro metal gear motor to get the desired force.

$$PID - Term = K_p . e(t) + \int_0^\tau K_i . e(t)dt + K_d . \frac{de(t)}{dt} \qquad (5)$$

2.6 Handle Design

The software SolidWorks 2018 was used to design the 3D system model. The handle was designed to hold the load cell in order to measure the force applied by the patient's hand. The maximum lever length measured from the shaft's rotation axis is 70 mm. The rotation degree of the system is 45 degrees from normal line. The SolidWorks file for the handle is converted to STL file for 3D printing. Ultimaker Cura software is an open source G-code generator and used to convert STL file to G-code for 3D printer. The load cell is mounted to handle that been designed as shown in Fig. 3. The arrow on the load cell should point down to the direction of the handle will move when a force is applied. There must be a spacer between the fixed surface and the load cell. This is because load cell is a specially shaped metal parts that have strain gauges' glue to them [23]. The strain gauges are resistors that change their resistance when they are bent. When the metal part bends, the resistance of the load cell changes, so the small change in resistance can be measured accurately. The patient's force would be transferred directly to the fixed surface without affecting the load cell if there is no space.
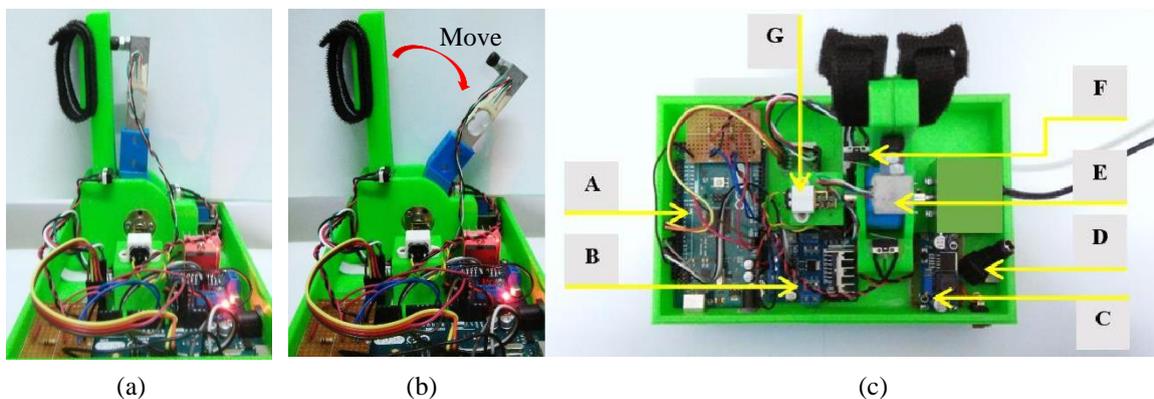

(a)   (b)   (c)

Fig. 3 - (a) The handle at origin; (b) When the handle moving forward; (c) Inside view (Table 1 for details)

Table 1 - Label of parts

| Label	Parts
A	Arduino Mega
B	Motor Driver
C	DC Step Up
D	12V DC Power Supply
E	Load Cell
F	Limit Switch
G	Micro Metal Gear Motor

3. Results and Discussions

The performance of one DOF haptic device is tested with P Controller, PI controller, PD controller and PID controller at the end of development process to obtain the best proposed controller. The haptic device without the controller is used as reference for selecting the best controller based on the lowest mean square error value. MSE is use to ensure system can reach its final state quickly as well as steady state error is small. The MSE value can be calculated according to Equation 6.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(f_i - y_i)^2 \qquad (6)$$

where; n = The number of data points, f_i = The output data and y_i = Setpoint

1) Without Controller: The haptic device run without a controller as reference data to compare the result with P, PI, PD and PID controller. The output did not reach the setpoint which is 0.5 N. It only rises up to 0.3 N and the MSE value is 0.0523 as shown in Fig. 4 (a).
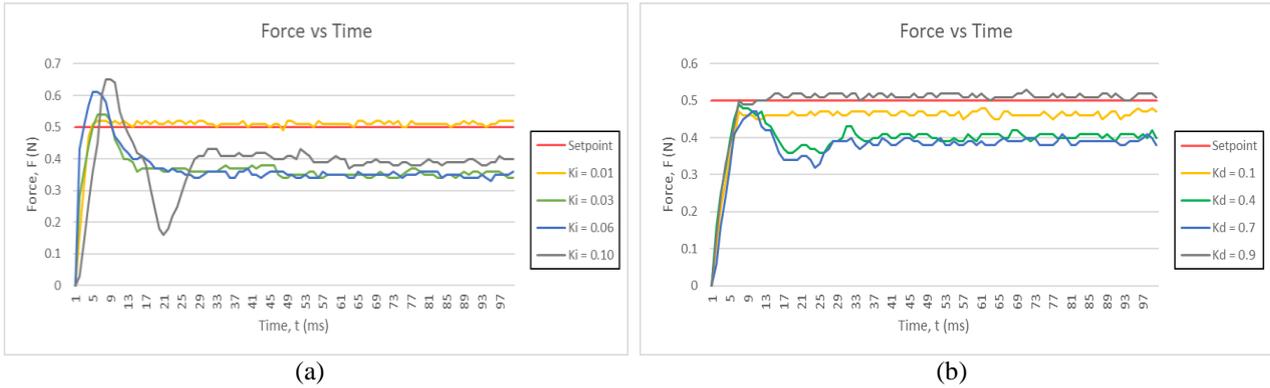
2) Proportional (P) Controller: The proportional gain (K_p) value was tested from 1.0 to 2.0. The motor will not be moving if the K_p value was set less than 1.0. As the K_p value increases, the speed of gear motor increases and graph shows more overshoot produces. Based on MSE value, the small value produces the best fit graph. Therefore, the best K_p is 1.3, with MSE value of 0.078. Fig. 4 (b) shows graph for the haptic device run for P Controller with different K_p value, which are 1.0, 1.3, 1.7 and 2.0 respectively.

| (a) | (b) |
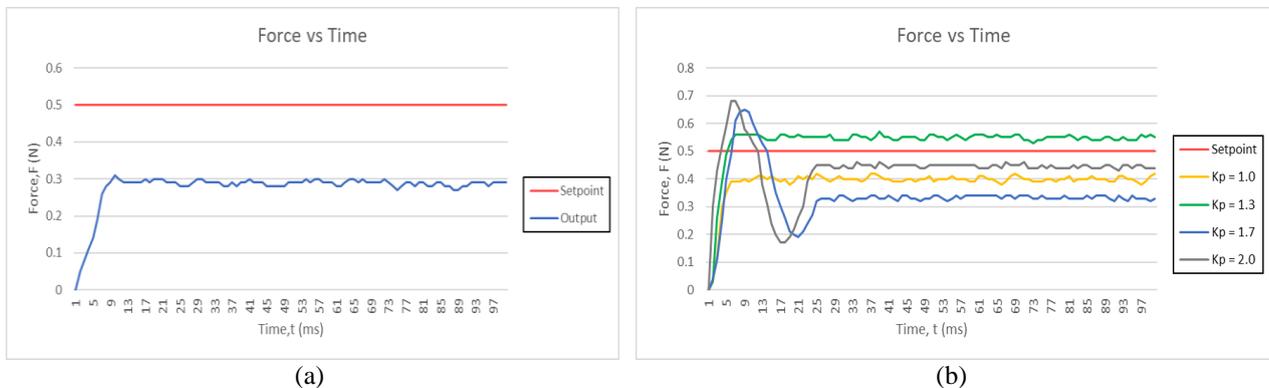
Fig. 4 – (a) The graph for haptic device run without controller; (b) The graph for P controller with K_p of 1.0 (MSE=0.016), 1.3 (MSE=0.078), 1.7 (MSE=0.035) and 2.0 (MSE=0.0134)

3) Proportional-Integral (PI) Controller: The proportional gain (K_p) was set as 1.3 obtained from P Controller. The integral gain (K_i) value was tested from 0.01 to 0.10. There is no effect when the value used was less than 0.01. Setting the K_i to less than 0.01 makes the micro metal gear motor move very slowly while it moves vigorously when set to more than 1.0. The speed of gear motor increases as the K_i increases. The rise time also increases but it produces higher overshoot. The best fit graph chosen based on MSE value. Therefore, the best K_p and K_i value are 1.3 and 0.01 respectively, with MSE value of 0.0041. Fig. 5 (a) shows graph for the haptic device run for PI Controller with different K_i values, which are 0.01, 0.03, 0.06 and 0.10.

4) Proportional-Derivative (PD) Controller: From P Controller, the proportional gain (K_p) was set as 1.3. The derivative gain (K_d) value was tested from 0.1 to 1.0. The K_d value is set less than 0.1 made the micro metal gear motor moving very slowly while it move faster if set more than 1.0. The steady-state error reduces as the K_d increases. The output mostly near to the assigned setpoint which is 0.5 N. The best fit graph chosen based on MSE value. Therefore, the best K_p and K_d value are 1.3 and 0.9 respectively, with MSE value of 0.0052. Fig. 5 (b) shows graph for the haptic device run for PD Controller with different K_d values, which are 0.1, 0.4, 0.7 and 0.9.

(a) (b)

Fig. 5 – (a) The graph for P1 controller with K_p = 1.3 and Ki = 0.01 (MSE=0.041), 0.03 (MSE=0.0213), 0.06 (MSE=0.0218) and 0.10 (MSE=0.0220); (b) The graph for PD controller with K_p = 1.3 and K_d = 0.1 (MSE=00690), 0.4 (MSE=0.0137), 0.7 (MSE=0.0191) and 0.9 (MSE=0.0052)

5) Proportional-Integral-Derivative (PID) Controller: From PI Controller, the proportional gain (K_p) and integral gain (K_i) is set as 1.3 and 0.01 respectively. The derivative gain (K_d) value was tested from 0.1 to 1.0. The steady-state error reduces for this controller and gives better result compared to P, PI and PD controller. The graph rises smoothly up to the assigned setpoint of 0.5 N. The controller makes the control loop respond faster with less overshoot. The best fit graph chosen based on lowest MSE value. Therefore, the lowest MSE value is 0.0028 obtained from K_p of 1.3, K_i of 0.01 and K_d of 0.2. Fig. 6 (a) shows graph for the haptic device run for PID Controller with different K_d value, which are 0.2, 0.4, 0.6 and 0.8 respectively.

In the P Controller, when the gain increases, the rise time decreases and there is a presence of overshoot as this controller only responds to change in error. Small K_p was the best approach to get to setpoint, but the performance will be slow proved by the decrease in rise time. A low steady state error and good transient response were hard to achieve using only proportional control. Thus, the integral and/or derivative gain must be included in the controller to get a better response.

For the PI controller, the rise time decreased slightly but the overflow and settlement time increased as the gains increase. The steady state error changed significantly as the integral gain existed in the controller. The PD Controller help to speed up the rise time as the gain increased and minimize the overshoot. However, it does not eliminate steady state error as only proportional and derivative gain is present. The stability of the device improved with this controller.

The PID Controller has minor decrease for rise time, overshoot, and settling time. There is no change in steady state error. A comparative study was carried out on the P, PI, PD and PID controller, in which the PID controller provides a good response than any other controller based on the lowest MSE value. Fig. 6 (b) shows the comparison between all controllers. The performance of the haptic device without any controller and with different types of controller are shown in Table 2. The highest value of MSE happened when haptic device tested with no controller (MSE = 0.0523). The output cannot reach the desired forced which is 0.5 N. Therefore, the haptic device was tested with different other type of controller to obtained the assigned setpoint. Based on the value of MSE of 0.0028, the proposed controlled for one DOF haptic device is PID Controller.

(a) (b)
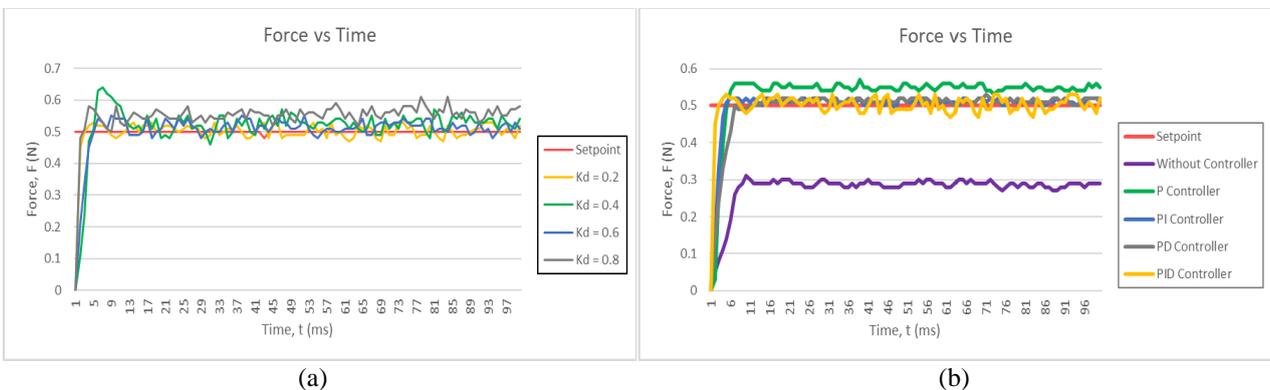
Fig. 6 – (a) The graph for PID controller with K_p = 1.3, K_i = 0.01 and K_d = 0.2 (MSE=0.0028), 0.4 (MSE=0.0065), 0.6 (MSE=0.0042), 0.8 (MSE=0.0058) and 1.0 (MSE=0.0077) and The graph for all controller, P, PI, PD and PID.

Table 2 - The Comparison Between Type of Controllers and Value of MSE

	K_p	K_i	K_d	MSE
No Controller	-	-	-	0.0523
P Controller	1.3	-	-	0.0078
PI Controller	1.3	0.01	-	0.0041
PD Controller	1.3	-	0.9	0.0052
PID Controller	**1.3**	**0.01**	**0.2**	**0.0028**

4. Conclusions

The force control for one DOF haptic device using PID Controller has been developed by following the system architecture. The mechanical haptic device consists of a motor driver, 12V micro metal gear and a handle attached to the load cell to provide a force measuring input that allows the motor to be more precisely controlled to give the patient the desired haptic sensation. In the meantime, a suitable PID Controller is obtained through evaluating the performance with that of the P, PI, PD controllers and with no controller based on the lowest value of the MSE which the best fit graph is 0.0028. A computer is used to compute the desired force based on the PID controller. The graph displayed can justify whether the proposed controller reach the assigned setpoint or not in real-time. Force control is the key component, because it imitates the grasping movement independently of the patient. The desired force is controlled and the force is measured in real-time to recognize the feedback control.

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