

An experimental study for grasping and pinching controls for an underactuated robotic finger using a PID controller

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Abstract. The empirical position control of an underactuated robotic finger is presented in this study. A proportional integral derivative (PID) control system for a robotic finger was introduced to control grasping of cylindrical objects with sizes in the range 30 to 60 mm, as well to control pinching for a range of objects. The robotic finger was made of two four-bar linkages connected in series. The second finger phalanx was modified by adding a DC motor at the coupler link of the second four-bar linkage so that the length could be varied to achieve a similar configuration to human fingers throughout the grasping and pinching operations. The maximum length was used for the grasping configuration, while the minimum length was used for the pinching configuration. The main objective of the proposed control process was to control grasping and pinching for different objects precisely enough to avoid both slipping and damage. An Arduino Mega 2560 was used to control the position of the DC motor movement to reach a predefined position for each specified object. The PID parameters were chosen empirically based on past experience and on repeated experiments, refined through trial and error. The proposed PID controller gave appropriate responses for the control system because of the proper choice of controller parameters

1. Introduction

In recent decades, there has been increased interest in the design and control of underactuated mechanical system used in robotic fingers; such a system has a number of actuators that is lower than the degrees of freedom [1]. Robotic fingers can be used to perform numerous tasks such as pick-and-place, and one possible approach to minimize the complexity of robotic finger mechanisms is to reduce the number of actuators to produce more efficient, simpler, and more reliable systems over fully actuated alternatives [2]. The main objective of the control process investigated in this work is to control the grasping and pinching of multiple objects with different dimensions with the correct amount of force to avoid slipping or damage to the grasped object. The proposed Proportional-Integral-Derivative (PID) control method is utilised in industrial control, and the popularity of these PID controllers can be imputed partially to their robust functional simplicity and conditions of operating, which facilitate use in an easy, straightforward manner [3].

2. Literature review

Pham Thuc Anh et al. [4] explained the dynamics pinching as a motion whereby a rigid object was grasped by multi-degree of freedom fingers with soft fingertips, described by a system of nonlinear differential equations with two algebraic constraints. It was thus shown that the dexterity of motion is realised based on a linear superposition of feedback signals of position, rotational angle, moments, and contact forces. The analytic result by numerically solving the system of 9- or 10-second order differential equations demonstrated the influence of closed-loop control schemes as introduced in that research and emphasised the applicability of dexterous multi-fingered robotic hands with soft fingertips in the dexterous manipulation of different objects. Biagiotti et al. [5] also presented



modelling and control of a robotic hand. The normal and tangential stiffness of soft materials were empirically studied to quantify their appropriateness for the expansion of soft pads for robotic hands. A control process was proposed to retain the desired stiffness of the grasp. In spite of the use of soft elements, such as the pads, the control strategy allowed an extremely rigid grasp by utilising the non-linear relationship between the imposed load and the compliance of the visco-elastic material of the pads.

An experimental study on position control for the underactuated robotic finger for light weights and small size through non-contact motion was presented by [6]. The Proportional Integral Derivative (PID) controller was chosen to control the position of the robotic finger for pinching and self-adaptive grasping capabilities during non-contact motion; the robotic finger was made of a seven bar linkage mechanism with a slider in the middle phalanx for pinching tasks. The position tracking for the angular displacement of the input link under the PID algorithm was satisfactory, but the RLS based FEL controller provided more accurate results, as it overcome the uncertainties presented. The controller error was equal to the difference between the actual and reference angular potentiometer.

Ali reza Khodayari et al [7] proposed a control algorithm design which allowed a system of shape memory alloy actuators in the prosthetic fingers with three degrees of freedom that included a PID-fuzzy controller. The gains of controllers were set, and the current applied to shape the memory alloy wires had minimum overshoot; the output of the system also had a minimal time to achieve stability. The simulation results as compared with actual measured data showed how well the controllers decreased the overshoot and the time to stability of the input signal shaping the memory alloy wires.

Ting Zhang et al [8] presented a multi-sensory prosthetic hand with an 11-degrees-of-freedom system. The hand had five fingers, and each could be moved separately using the embedded motor. The system of control was mounted in the palm. Each finger had two degrees of freedom and two joints, and the artificial hand as a whole was controlled by a multiprocessor controller based on a field programmable gate array (FPGA) and digital signal processor (DSP). The system of control consisted of palm and finger control systems, and the control system for each finger was incorporated at the fingertip. This hand was guided by electric signals, and strategies of hierarchical shared control were applied. Impedance control allowed the fingers to work as authentic springs. The empirical results noted that patients were allowed to work the equipment to develop strategies of hierarchical control successfully, and the success of grasping increased with increases in interactive control.

In this study a proposed underactuated robotic finger with a variable coupler link length of the second four-bar linkage, using DC motor with a screw and coupling system impeded on the second phalanx, was introduced to accomplish grasping and pinching operations. Torsional springs were mounted in joint two and three to enable the mechanism of the underactuated robotic finger to be specified. These springs were fixed appropriately for the direction of the motors for grasping operations and the motors can be reversed for object release in a way that mimics the human hand. A PID controller was used to train the DC motor with a multi potentiometer to perform grasping and pinching operations for different specified objects.

3. Underactuated robotic finger description

The proposed underactuated robotic finger mechanism has three phalanges consisting of two sets of four-bar linkages. Referring to figure (1), the underactuated robotic finger was composed of a DC motor that moves the finger in two directions; the finger moves forward to either grasp or pinch the object then releases the object when moving backward. This motor was tied to a power screw and coupling to transform the rotational motion of the DC motor to linear motion, and the motor and the power screw were mounted to the finger using a bearing housing.

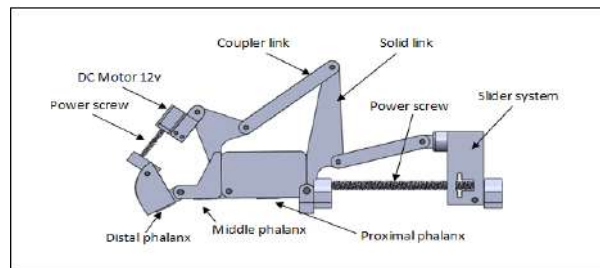


Figure (1): Robotic Finger Diagram

The slider- crank mechanism is accelerated by the DC motor to translate the slider's linear movement into rotational movement. Then, the first four-bar linkage accelerates to act as the mechanism of transmission to move the first phalanx of the finger, moving the second four-bar linkage to move the second phalanx and the third phalanx, which represent the output link of the second four-bar linkage. Another DC motor with a screw and coupling system was mounted on the copular link of the second four-bar linkage in order to adjust its length in either grasping or pinching configuration. The maximum length was used in grasping configuration, while the minimum length was used in pinching configuration. Two springs were combined with the second and third joint to enable the robotic finger to adapt to the shape and the size of objects with different geometries being grasped or pinched. The dimensions of the robotic finger are shown figure (2); these were chosen according to the overall characteristics of the human finger.

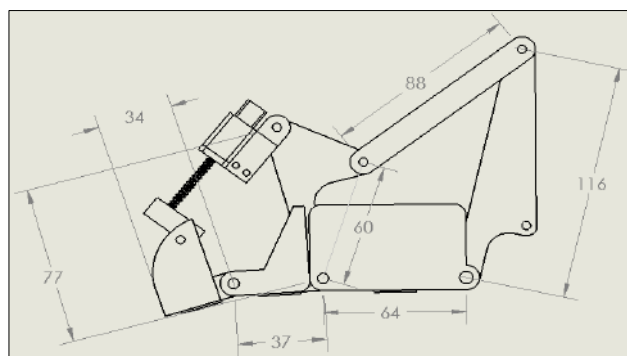


Figure (2): Dimensions of proposed underactuated robotic finger

4. Control system

The PID controller was implemented to control the robotic finger's tracking of the predefined desired position for each object for either grasping or pinching. The predefined positions for the selected objects were calculated through training the robotic finger to grasp these objects with sufficient but not excessive grasping forces to prevent damage or slipping. Cylindrical objects with a range of diameters from 30 to 60 mm were used for grasping and 40×40×10 mm objects were used for pinching.

The control system of the robotic finger consisted of two DC motors and one multi potentiometer equipped with a 9-volt DC motor, and an Arduino, a micro controller board was chosen to control the robotic finger to track the desired path. Arduino is an open source platform used for building electronics projects. Using this microcontroller is very popular, as using Arduino means there is no need to separate the hardware connections to load a new project program to the same board; it can simply be connected to a computer using a USB cable. Arduino also uses the simple version of C++ to develop control code.

One of the DC motors of the robotic finger control system was connected to the microcontroller to supply the input torque, while the other DC motor was used to reduce the coupler link length of the second four-bar linkage in the pinching configuration. In order to connect the DC motor with the Arduino, a monster motor shield driver was used. This driver is a full bridge driver used for a wide range of applications. The shield of motor is a driver module for motors that permits the use of Arduino to guide the direction and working speed of the motor. Based on a Drive Chip L298 (Dual Full-Bridge), it can drive two a DC motors. The motor shield is powered by the Arduino either directly or by an external power supply. Such modules can thus be utilised for the development of intelligent vehicles and micro robots. The motor driver connections with the Arduino microcontroller board are illustrated in figure (3).

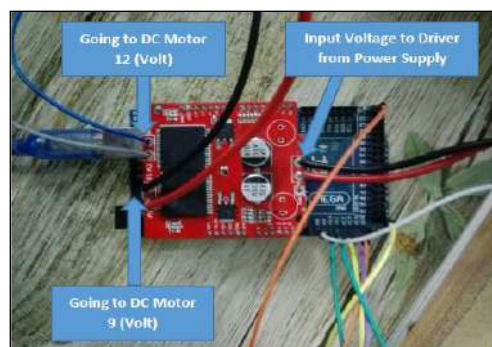


Figure (3): Monster Motor Shield connected to Arduino Mega 2560

5. Proposed Proportional-Integral-Derivative control

In this study, the proposed control of the PID controller determined the error value by subtracting the desired set point from variable measured. The PID controller thus attempted to minimise the error until reaching the set point by controlling the process by utilising a manipulated variable. The PID algorithm consists of three constant parameters or terms: proportional (P), integral (I), and derivative (D). The main characteristic of the PID controller is the ability to utilise the three control terms' effect on the output of the controller to find an optimal and accurate control level. The equation that describes the PID controller algorithm is [9]

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \quad (1)$$

where

$u(t)$: The output controller variable.

K_p : Proportional constant gain.

K_i : Integral constant gain.

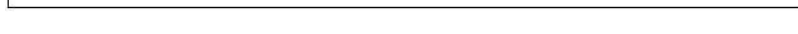
K_d : Derivative constant gain.

e : The error of the system can be getting by subtracted measured process variable from set point.

t : Instantaneous time.

τ : The variable of integration, it is the values from time zero to the present (t).

Figure (4) demonstrates the flow chart of the control process. The measured process value represents the instantaneous position of the slider position, which gives feedback to the control system along with the instantaneous error of the process. The proportional constant gain (K_p) relies only on the difference between the set point and measured variable. The proportional constant gain calculates the



A reasonable criterion for tuning the controller parameters (K_p, K_i & K_d) is that the control system

7. Experimental setup

The experimental setup of the robotic finger control system is displayed in figure (5). The control system of the robotic finger consisted of a PC, power supply, and the microcontroller (Arduino Mega 2560). The PC was loaded with the microcontroller software. The microcontroller read the signal from the multi potentiometer to give the instantaneous position of the slider mechanism to provide the system with the instantaneous error. The Monster motor shield driver was connected to the microcontroller and was utilised to guide the direction and working speed of the DC motors. A power supply was used to supply the current required for the control system.

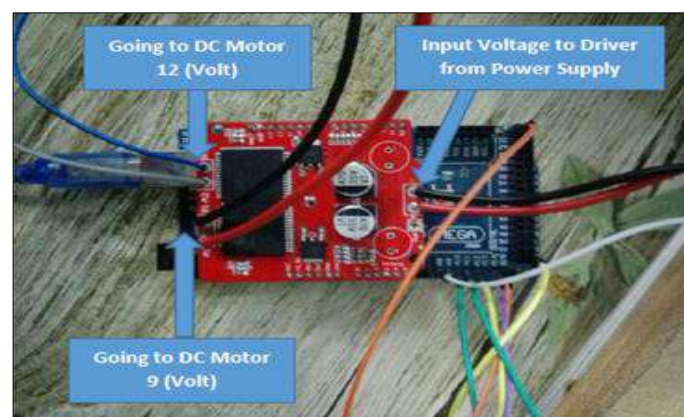


Figure (5): PID Control System

8. Experimental Tests

The proposed control system was used to train the robotic finger to grasp and pinch multiple objects with different sizes and shapes. The control code for the PID controller was written using Arduino software. The voltage reading of the potentiometers determined the motor position for each grasped or pinched object. For object (A), the DC motor accelerated the robotic finger manually until the finger grasped the object with the minimum force required to grasp stably; this reference was set by grasping the object manually as the multi potentiometer determined its position, recording the multi potentiometer's voltage to calculate the distance travelled by finger screw. These steps were repeated for the objects B, C, D, and E. In the pinching operation, it was first necessary to reduce the coupler link length of the second four-bar linkage to the optimised pinching length. After reducing the coupler link, object (F) was taken, and the DC motor used to accelerate the robotic finger until the finger pinched the object with the minimum force. The reference position was set by pinching the object manually as the multi potentiometer determined its position. These steps were repeated for object E. After recording all reference points for all the objects to be grasped or pinched, the control code was modified using the PID controller to control the position of motor movement for each object in each process; the PID controller accelerated the input DC motor to move the robotic finger to reach the desired recorded reference voltage, which represented the slider distance that the screw had to move to grasp the specified object for all objects in the grasping and pinching tasks. The return program moved the finger away and readied it to execute another task. The grasped and pinched objects are summarised in table (1).

Table (1): Object used for grasp and pinch actions

Object	Diameter (mm)	Weight (g)
A	30	20
B	35	25
C	40	30
D	50	35
E	60	42
Object F for pinching task (40*40*10) mm (L*W*T) (15g)		

9. Results and discussion

The PID controller in this study was governed using equation (1) to provide a feedback loop for the control system of the robotic finger. The reading of the multi potentiometer represented the output of the control system. Figure (6) shows the experimental results for object (A). The object diameter was 30 mm, and the multi potentiometer reading was 41 mm of slider distance. Figure (7) demonstrates the motor behaviour during grasping. This figure shows that the motor voltage supplied was decreased gradually until the finger held the object. Figure (8) demonstrates the PID control response during grasping the object (B). The multi potentiometer reading for an object of diameter 35 mm represented 37 mm. Figure (9) depicts the motor behaviour when the robotic finger grasped that object. Figure (10) represents the finger potentiometer reading during grasping object (C) of diameter 40 mm when the linear distance reading was 33 mm. Figure (11) shows the motor behaviour while grasping the same object. The multi potentiometer reading for object (D) of diameter 50 mm was 26 mm, as illustrated in Figure (12) and Figure (13) depicts the motor behaviour. Figure (14) displays the PID control response for the output signal while grasping object (E) of diameter 60 mm when the linear distance reading was 21.2 mm. Figure (15) demonstrates the motor behaviour when the robotic finger reached object (E). The linear distance reading for object (F) for the pinching task was 10 mm, as shown in figure (16). Figure (17) reveals the motor behaviour throughout the pinching task. Object (E) was used for pinching task and the multi potentiometer reading was 8.9 mm, as seen in figure (18). Figure (19) clarifies the motor behaviour. Figure (20) shows the grasping and pinching tasks for different objects. It can be seen that as the grasped object diameter decreased, the slider distance, which represented the finger movement, increased and vice versa, as the finger needed to move further to envelope smaller objects and grasp them precisely, while in grasping larger objects, the slider of the input torque of the robotic finger had to move a smaller distance to grasp the object with enough force to avoid slipping. Referring to figure (18), which represents the potentiometer reading during the pinching task for object (E), the distance travelled by the slider is much smaller than in the grasping tasks; because that pinching configuration is limited in comparison to the grasping configuration, as in the human finger. The response parameters of the control system are given in table (2), marked with the transient response specifications. Where systems that store energy cannot respond instantaneously, they exhibit a transient response when they are subjected to inputs or disturbances. Consequently, the transient response characteristics constitute one of the most important factors in system design. In many practical cases, the desired performance characteristics of control systems can thus be given in terms of transient response specifications. The rise time and settling time in the grasping tasks were greater than in the pinching tasks, as the input slider distance in grasping was larger than in pinching. The overshoot in all tasks was zero, leading to a steady signal during grasping and pinching all objects.

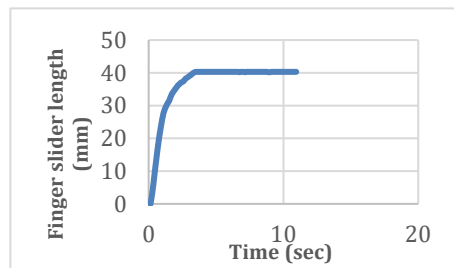


Figure (6): potentiometer reading of slider distance through grasping object (A)

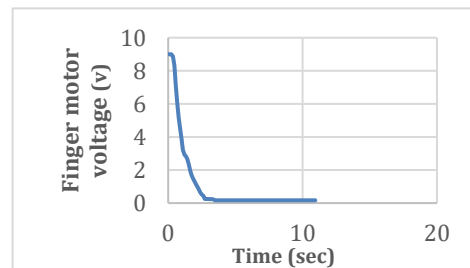


Figure (7): Finger motor behaviour through grasping object (A)

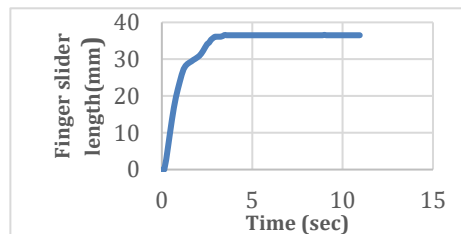


Figure (8): potentiometer reading of slider distance through grasping object (B)

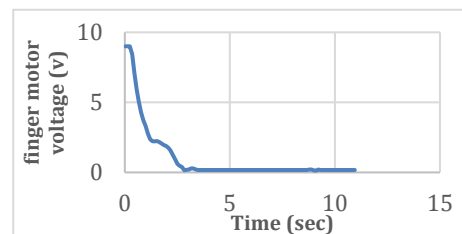


Figure (9): potentiometer reading of slider distance through grasping object (B)

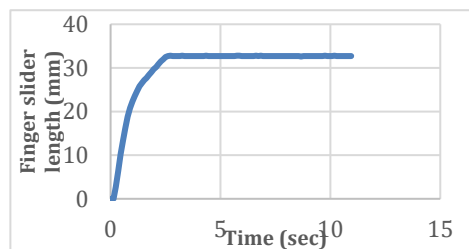


Figure (10): Finger potentiometer reading through grasping object (C)

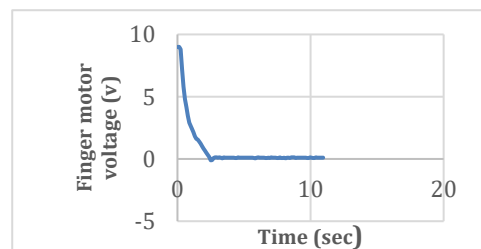


Figure (11): Finger motor behaviour through grasping object (C)

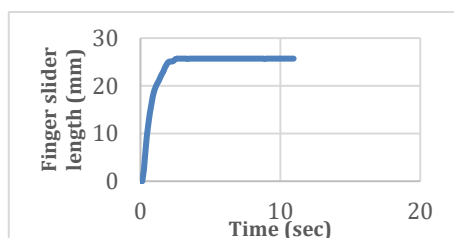


Figure (12): Finger potentiometer reading through grasping object (D)

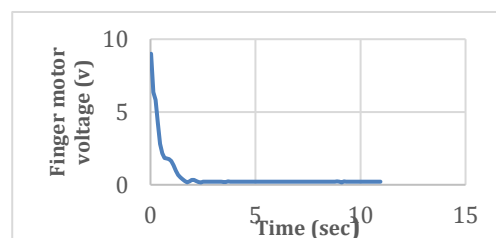


Figure (13): Finger motor behaviour through grasping object (D)

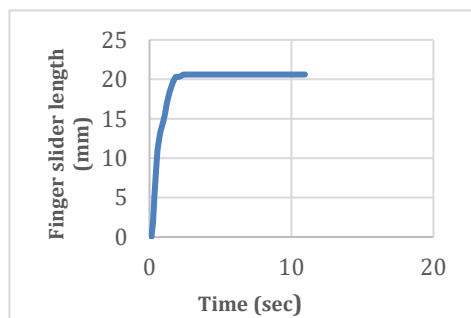


Figure (14): Finger potentiometer reading through grasping object (E)

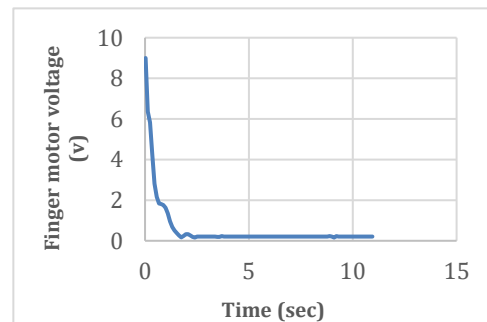


Figure (15): Finger motor behaviour through grasping object (E)

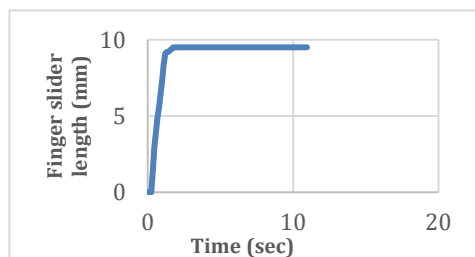


Figure (16): Finger potentiometer reading through grasping object (F)

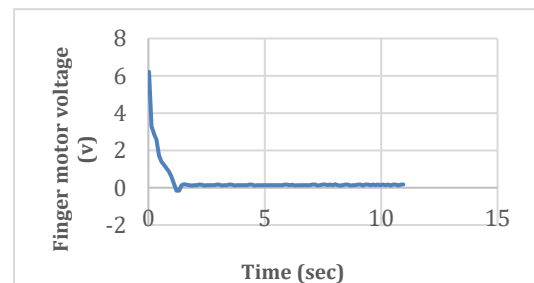


Figure (17): Finger motor behaviour through grasping object (F)

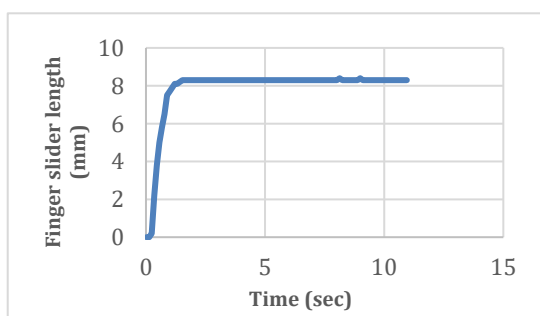


Figure (18): Finger potentiometer reading through pinching object (E)

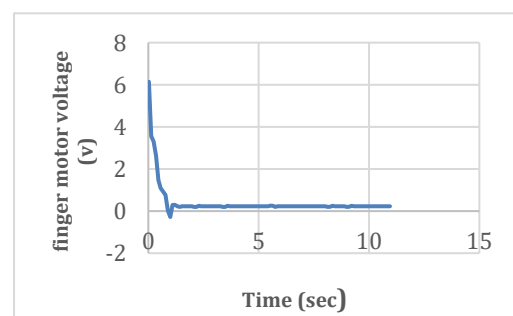
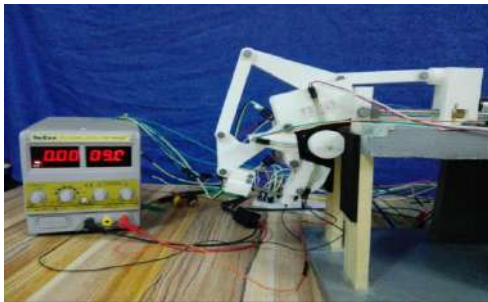
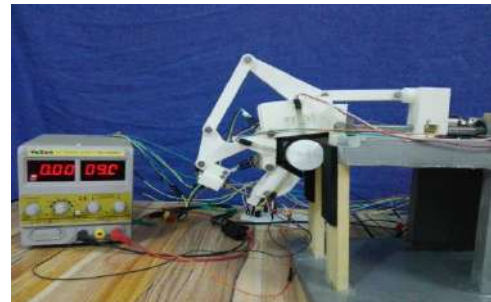
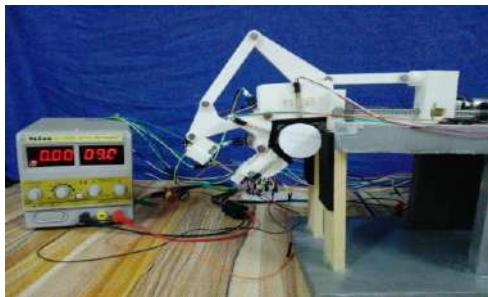
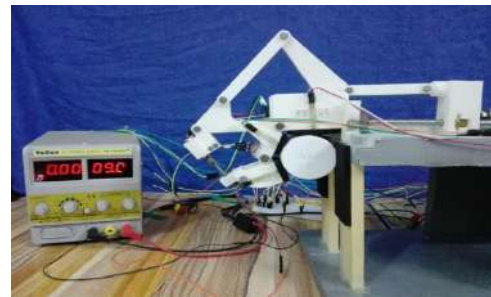
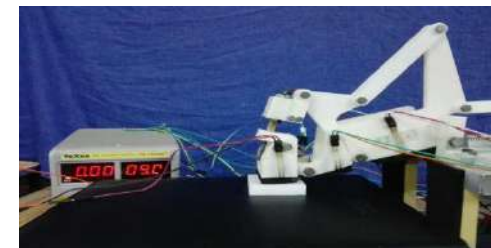
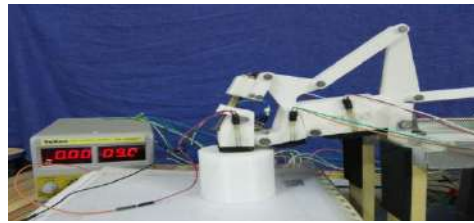


Figure (19): Finger motor behaviour through pinching object (E)

Table (2): Transient response parameter specifications for the grasped objects

Object	Object dimensions(mm)	Rise time (sec.)	Settling time (sec.)	Overshoot
A	Dia.=30	1.88	3.477	0
B	Dia.=35	2.156	3.477	0
C	Dia.=40	1.615	2.828	0
D	Dia.=50	1.398	2.612	0
E	Dia.=60	1.182	2.396	0
F	Height=60	0.749	1.751	0
E _{pinching}	Height=10	0.643	1.532	0

**Object A****Object B****Object C****Object D****Object E****Object F-pinching**



Object E- pinching

Figures (20): Grasping and pinching tasks for different objects

10. Conclusions

The proposed PID controller assigned an appropriate response for the control system of the robotic finger to track the desired path because of the proper choice of controller parameters. As seen in figures (6) to (12) the time taken by the robotic finger to complete both grasping and pinching tasks was about 2.5 seconds. The error throughout the control process was small, within a range of 0.5 to 0.7 mm, which confirms the success of the control process providing the minimum forces needed to grasp and pinch the required objects with a least possible error. The DC motor incorporated with a screw and coupling system to adjust the copular link length of the second four-bar linkage to perform grasping and pinching configurations accomplished the required operations with advantageous performance and took a relatively short time achieve the desired task effectively.

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