

Adaptive Grasp Force Control for Robotic Gripper Based on Force Sensitive Resistor Sensor

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ABSTRACT

Robotics technology has been developed to support human tasks through robotic grippers that can control force on fragile surfaces. This research presents the design of an adaptive grasp force control system for two types of robotic grippers using FSR sensor and a PID control approach. This system was developed to adaptively regulate grip force when interacting with objects with varying surface characteristics. Experimental results showed that the FSR sensors provided feedback with an average error of 0.112 N. Implementation of PID control using the Ziegler–Nichols method successfully enabled the robotic gripper to achieve a desired force of 5 N. The gripper type A demonstrated the settling time of 1.75 seconds for glass cup, 2.25 seconds for plastic cup, and 3.25 seconds for paper cup. Meanwhile, gripper type B demonstrated a settling time of 2 seconds for glass cup, 2.75 seconds for plastic cup, and 3.75 seconds for paper cup. Although the response is slower, the gradual increase in force can reduce the risk of applying excessive force to soft object surfaces. A comparison between the two gripper designs highlights the importance of mechanical structure in influencing control performance.



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1. INTRODUCTION

Robotic technology has been increasingly developed to assist or replace human mobility and manipulation tasks through the use of robotic arms. One of the most important components of a robotic arm is the end effector, which directly interacts with the workpiece or target object. End effectors are also used in industrial [1]-[2] and medical [3]-[4] applications. Depending on the intended task, an end effector may take the form of a clamp, welding torch, paint gun, or gripper. Among these configurations, grippers are commonly used for object manipulation because they can grasp, hold, and transfer objects from one location to another. The gripper consists of rigid fingers that can open and close. In industrial applications, grippers are used to pick up and place manufactured items, such as food, beverage bottles, and machine components [5]. The actuation system of a gripper can be driven by an electric motor or pneumatic mechanism, which provides the force required to hold the object. Ideally, a gripper should

perform similarly to a human hand by applying sufficient force to securely hold an object while avoiding excessive force that may cause damage.

Although conventional grippers can effectively perform repetitive grasping tasks under controlled conditions, they may have difficulty handling objects with varying shapes and surface conditions [6]–[7]. In particular, insufficient force may cause the object to slip or fall, whereas excessive force may deform, dent, or break the object. Therefore, adaptive control methods can be employed to address this problem. For example, Proportional Integral Derivative (PID) control has been widely used in robotic systems because it can adjust the control response [8]–[11]. Such force regulation is relevant for grasping tasks involving objects with varying surface conditions.

In addition to the control strategy, the mechanical configuration of the gripper can influence its grasping capability. The gripper configuration is inspired by the structure of the human hand, which consists of fingers. For the purpose of grasping objects, most tasks utilize two- and three-finger grippers. During a grasping operation, the fingers may be actuated individually or simultaneously depending on the mechanical configuration. Syafeeza [12] demonstrated a gripper mechanism with multiple degrees of freedom (DOF) for grasping movements. To achieve flexible gripping movements, the gripper's fingers are designed to move together. Grippers with parallel finger configurations are designed with simple mechanisms and controls. Davar [13] developed and assembled a dual-jaw gripper for grasping tasks. This gripper consists of symmetrical parallel segments that move together to align and hold objects.

However, the mechanical of a gripper does not necessarily guarantee appropriate regulation of the force applied to the object. The design of a gripper, which is installed as an end effector for gripping tasks on objects with certain surfaces, requires additional devices such as sensors. Sensors placed on the gripper's fingers are crucial for assessing the surface condition of the object in direct contact with the gripper. One proposed method to control the gripper's force in object-grasping tasks is using force sensors. As explained in Payo [14], force control is required on the gripper when interacting with the target object, with a limit on the force applied to the object to prevent damage to its surface. An embedded force sensor device to detect the strength of the robotic hand's gripping force is integrated with a microcontroller. This method can benefit a robotic arm system with a gripper, because it reduces the risk of either dropping or damaging the grasped object.

A Force Sensitive Resistor (FSR) sensor is one type of sensor that can be used to detect applied force through changes in electrical resistance [15]. Differences in force on the sensor produce different resistance values. The FSR sensor is a simpler sensor for controlling gripping force by monitoring the detected force, similar to a human hand. The FSR sensor is placed at the fingertips of the gripper. Because of the difference in resistance values, this sensor can be used as a reference to adjust the grip strength. When the gripper contacts an object, the FSR sensor detects the resulting force and provides feedback to the controller. The measured response can then be used as a reference for adjusting the gripping action or limiting the applied force to a predefined threshold.

Although previous studies have investigated different gripper configurations and force-sensing approaches, the relationship between gripper design and adaptive gripping-force performance remains insufficiently explored. Existing studies have generally focused either on developing mechanical gripper mechanisms and on implementing force-control and sensing techniques, while comparative evaluation of different gripper configurations under the same force-feedback mechanism has received less attention. This study aims to design an adaptive grasping force control system for two robotic gripper designs to regulate the force applied during object grasping and compare their grasping performance and suitability for handling objects with different characteristics.

The main contributions of this research are twofold: (1) the development and implementation of an FSR sensor based adaptive grasping-force control method for regulating the force applied by a robotic gripper, and (2) a comparative experimental evaluation of two different gripper mechanism designs under the same force-feedback control framework when grasping objects with different surface and material characteristics.

2. RESEARCH METHOD

This research began with the design of an adaptive grasp force control system for the robotic gripper. It then continued with the design of the robot's gripper mechanics, followed by the development of a control algorithm to adaptively regulate the robot's grip force using an FSR sensor. Experiments were conducted to test the system's performance in stably grasping various objects.

2.1 Block Diagram of Robotic Gripper

This research began with the design of an adaptive grasp force control system for the robotic gripper, as shown in Figure 1. The proposed robotic gripper design is used as an end effector for grasping objects with a two-finger mechanism. The gripper has a simple structure with a parallel-finger arrangement, enabling it to handle objects of varying shapes and sizes within a specific range. The gripper is able to handle objects with shapes and sizes within a certain range. The actuator in the form of a servo motor is used to move the gripper fingers to open and close. In the implementation of the system for the task of grasping objects, the surface of the object being grasped has a variety of capabilities to withstand the force of the resistive forces. In the design, the sensor that detects the force when the gripper finger touches the object uses a force-sensitive resistor (FSR) sensor. A microcontroller is used to process the sensor data and execute the adaptive grasp force control algorithm. The control system determines when the gripper should stop closing based on the detected grasping force. In this study, the objects used for the grasping experiments were cups made of three different materials: glass, plastic, and paper.

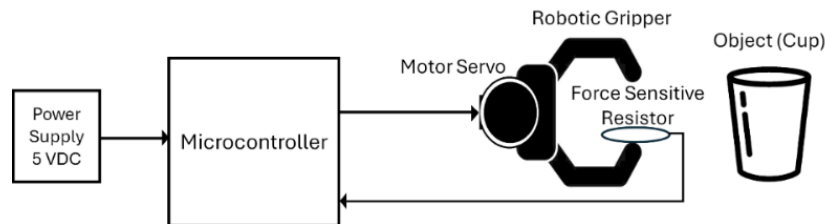


Figure 1. Block diagram robotic gripper

2.2 Robot Gripper Mechanism Design

The dimensions of the objects to be grasped were determined before the system was developed and used as a basis for designing the proposed robot gripper. Two distinct robot gripper mechanisms, namely a direct-driven mechanism (Type A) and a linkage-based mechanism (Type B), were developed to investigate the influence of mechanical configuration on grasping-force control performance under different object characteristics. The objects consisted of glass, plastic, and paper to evaluate the performance of the robot gripper. The reason for choosing these objects is because they have different surface sensitivities when the gripper's fingers touch the object's surface. The two proposed robot gripper mechanisms feature a two-finger structure that moves simultaneously during the opening and closing motions, as shown in Figure 2.

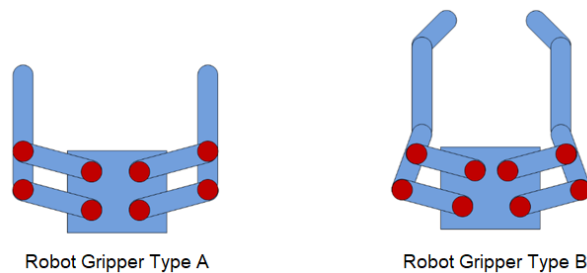


Figure 2. Robot gripper type A and type B

The design of a robotic hand from two two-finger gripper models connected in parallel for gripping cylindrical objects, such as glasses, with diameters ranging from 4 to 6 cm. The gripper structure material was fabricated from 4-mm-thick acrylic material. In the design of this two-finger gripper model,

has one degree of freedom (DOF) through an angular range of 45°. For type A gripper, the dimensions are 90mm x 48mm x 46mm with a gripper width of 45mm. For type B gripper, the gripper dimensions are 140mm x 50mm x 50mm with a width of 130mm. A servo motor was used as the actuator to drive the connecting and transmission mechanism to grasp and release the object. The hardware configurations of both two-finger grippers are shown in Figure 3.

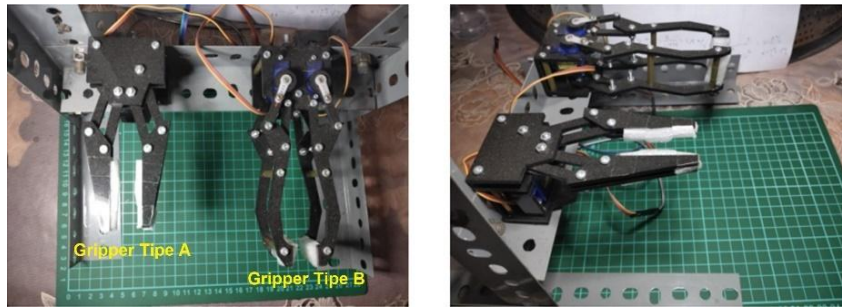


Figure 3. Two-finger gripper construction hardware

2.3 Force Sensor Calibration

The force sensor used for feedback is a force-sensitive resistor with of a 7.6 mm diameter polymer thick film, specifically the FSR-400. The FSR-400 has a force sensitivity range between 20 to 2000 grams (0.2 to 20 N). However, in this study, the applied force was limited to approximately 500 grams (4.91 N). The FSR-400 was installed on the gripper robot to measure the contact force between the object surface and the gripper fingertips. The sensor converts changes in resistance into voltage using a voltage-divider circuit. To acquire the sensor data, the FSR-400 was connected to a 1 kΩ resistor in the voltage-divider circuit. The output voltage was calculated using (1).

$$V_{out} = V_{in} \times \frac{R_1}{R_1 + R_{fsr}} \quad (1)$$

Where V_{in} is the supply voltage for the FSR sensor, which is 5 V. V_{out} is the output voltage of the voltage-divider circuit, calculated using a 10 kΩ resistor (R_1) and the resistance of the FSR sensor (R_{fsr}). The voltage value signal V_{out} is then used to initialize the microcontroller program on the Arduino Uno as shown in Figure 4.

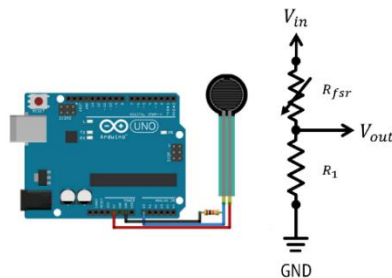


Figure 4. FSR sensor with Arduino UNO circuit diagram

The relationship between tension and load force required to grip an object is expressed in terms of force (N) using Equation (2). This process is performed during the calibration step which produces data presented in Table 1. Then the measured force values are then used to determine the set-point values in the program. Next, it is used to provide instructions to the hardware by controlling the servo motor on the robot's hand. In this context, m represents mass, which is measured in grams for force calibration and g is equals 9.81 m/s².

$$Force(N) = m \cdot g \quad (2)$$

Based on the force sensor calibration results presented in Table 1, it can be seen that at 0 grams, the sensor produces no voltag output from the voltage comparator circuit. In the range of 100-200 grams, the output voltage increases significantly, indicating that the sensor is highly responsive to changes in the applied force. However, in the range of 400-600 grams, the increase in output voltage becomes smaller, indicating that the sensor is approaching its saturation point. Therefore, to ensure reliable and

sensitive force measurement, the maximum force applied by the robotic gripper in this study was limited to 500 grams (4.91 N).

Table 1. Result of force sensor calibration

Object weight for force calibration (g)	Calculated force (N)	Voltage Output(V)
0	0.00	0.00
100	0.98	1.67
200	1.96	2.50
300	2.94	3.12
400	3.92	3.45
500	4.91	3.70
600	5.89	3.85

2.4 Gripper Robot System Programming

The robot gripper system is programmed to move and grip objects according to the setpoint value using PID control to stabilize the force. The system uses a microcontroller to control the movement of the servo motor with a PWM signal and reads the FSR sensor data. Figure 5 shows the flowchart of the programming design of the robot gripper system. When the FSR sensor reading reaches the setpoint value, the gripper stops moving and maintains its clamping position. By applying the FSR sensor as a force setpoint and using PID control, the robot gripper movement can be regulated to prevent excessive force and potential damage to the object's surface.

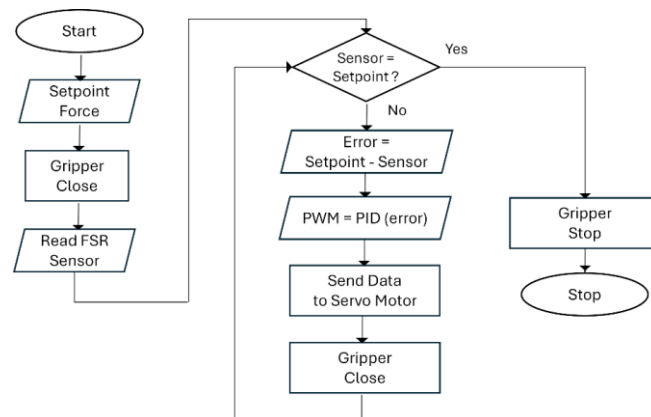


Figure 5. Flowchart of gripper robot system

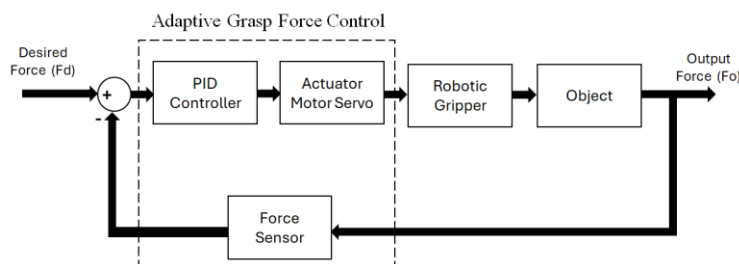


Figure 6. Block diagram of grasp force control

2.5 Grasp Force Control Design

Figure 6 shows a block diagram of grasp force control using Proportional-Integral-Derivative (PID) control applied to the robot's gripper via a servo motor. The purpose of controlling the servo motor during the gripping process is to achieve a stable gripping force when the gripper's fingers contact the object according to the desired force (F_d) setpoint. The output force (F_o) is measured by the FSR sensor, which provides feedback in the form of the measured force values.

During the design step of grasp force control, the PID controller is tuned using the Ziegler – Nichols method according to the tuning rules presented in Table 2. Determination of the PID controller parameters (K_p , K_i , and K_d) is based on an analysis of the unit step response characteristics of the regulated plant.

Table 2. Controller parameters for Ziegler-Nichols method

Controller	K_p	T_i	T_d
P	$0.5K_u$	-	-
PI	$0.45K_u$	$P_u/1.2$	-
PID	$0.6K_u$	$P_u/2$	$P_u/8$

In this method, to obtain K_u and P_u for continuous oscillation, a proportional control action is applied with $T_i = \infty$ and $T_d = 0$. Here, K_u is the gain when the system starts to exhibit sustained oscillation, and P_u is the oscillation period. The relationship between these parameters with K_i and K_d can use (3) and (4).

$$K_i = \frac{K_p}{T_i} \quad (3)$$

$$K_d = K_p \cdot T_d \quad (4)$$

In the experimental process, testing was conducted with a setpoint of 5 N. The first test was conducted on a Type A gripper. The resulting system yielded a K_u value of 5 and the P_u value is 3 seconds. Therefore the K_p , K_i , and K_d values were determined using calculations based on the Ziegler Nichols PID controller method. From the calculations and responses of the plant above, the obtained values of K_p is 3, K_i is 2 and K_d is 1.12.

The second test, conducted on a Type B gripper, also applied a gripping force setpoint of 5 N. The results yielded the K_u is 4 and the P_u is 2 seconds. The calculated K_p , K_i , and K_d values were 2.4, 2.4, and 0.6, respectively. These values were then entered into the microcontroller program.

2.6 Performance Evaluation of Robotic Grasping System on Various Objects

To evaluate the performance of the robotic grasping system on various objects, the test consisted of two parts: evaluating the gripping characteristics of the Type A gripper during gripping and testing the characteristics of the Type B gripper during gripping. To determine the grasp force control characteristics of the gripper system, the changes in the sensor force value changes as the gripper moved toward the closed position while grasping the object. The gripper stopped moving when the measured force reached the reference force threshold. Three types of objects were used: glass cups, plastic cups, and paper cups, as shown in Figure 7.



Figure 7. Glass cup, plastic cup, and paper cup objects

3. RESULTS AND DISCUSSION

To evaluate the performance of the proposed system, a series of experimental tests were conducted focusing on the accuracy of the force sensor and the effectiveness of PID based force control applied to the robot gripper. The evaluation was divided into FSR sensor accuracy testing, PID control performance testing of the Type A gripper and Type B gripper.

3.1. Testing the Accuracy of the FSR Sensor

To evaluate the accuracy of the force measurements obtained from the sensor, this test was conducted to determine the success of the system in obtaining the FSR sensor value when the sensor

touches and presses the object's surface. Comparison of the calculation results and response analysis using the force sensor against the reference pressure was carried out with different values. The results of the FSR sensor accuracy test are presented in Table 3.

Table 3. The accuracy of the FSR sensor force value

Testing	Weight Reference (g)	Force Reference (N)	Measurement Force (N)	Error (N)
1	300	2.94	2.80	0.14
			3.02	0.08
			2.90	0.04
2	400	3.92	4.05	0.13
			3.85	0.07
			3.95	0.03
3	500	4.91	5.10	0.19
			4.80	0.11
			4.95	0.04
4	600	5.89	6.20	0.31
			5.75	0.14
			5.95	0.06
Average error				0.112

The results show that the FSR sensor exhibited an average measurement error of 0.112 N, indicating a relatively good level of accuracy for force measurement. It is apparent that the error tends to increase at higher forces, especially in the 600 grams (5.89 N). This behavior can be attributed to the nonlinear characteristics of the FSR sensor and its sensitivity to changes in the applied force. Despite this limitation, the sensor provided a stable response over the tested force range and was considered suitable as a feedback system in the robot gripper force control system.

3.2. Testing the PID Control of the Gripper Type A

The force control performance of the Type A gripper was evaluated while gripping an object. This test was conducted to determine the response of the adaptive grasp force control implemented in the system. The control test applied a set point with a grip force of 5 N for commands to the microcontroller. The PID parameters used for the Type A gripper were ($K_p = 3$), ($K_i = 2$), and ($K_d = 1.125$). To determine the response when the gripper type A grips a glass cup, a plastic cup and a paper cup with the same setpoint. The force response of the Type A gripper when gripping the glass, plastic, and paper cups is presented in Figures 8, 9, and 10, respectively.

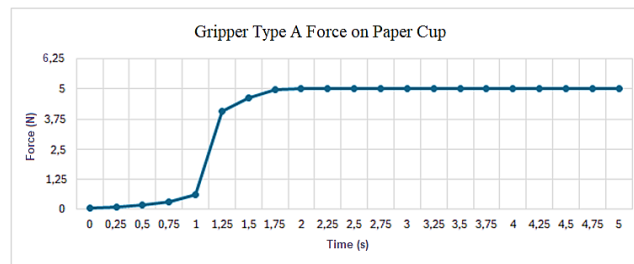


Figure 8. Response graph of gripper type A force on glass cup

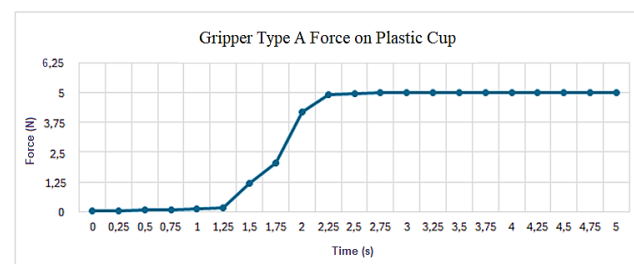


Figure 9. Response graph of gripper type A force on plastic cup

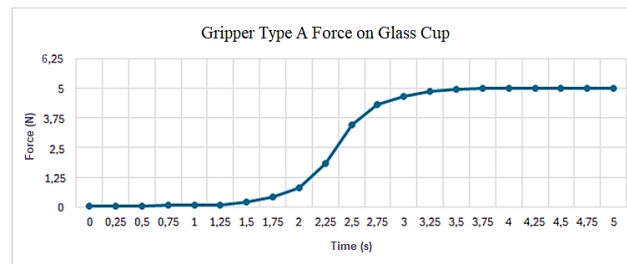


Figure 10. Response graph of gripper type A force on paper cup

Based on the force response graphs shown in Figures 8, 9, and 10, the Type A gripper was able to track the specified force setpoint, although the response characteristics varied depending on the object being gripped. In the glass cup test, the force response increased rapidly at approximately 1 second and reached the 5 N setpoint at 1.75 seconds, as the rigid surface of the glass cup allowed the applied gripping force to be transmitted effectively to the FSR sensor. In the plastic cup test, the system exhibited a slightly slower response, with a settling time of 2.25 seconds, due to the greater deformability of the plastic material, which affected the transmission of the gripping force to the sensor. Meanwhile, the paper cup produced the slowest response, with a settling time of 3.25 seconds, as its soft and easily deformable characteristics reduced the rate of force transmission to the sensor and consequently required more time for the controller to reach the specified force setpoint.

3.3. Testing the PID Control of the Gripper Type B

Testing the force response of Type B gripper was evaluated using the same three types of objects: a glass cup, a plastic cup, and a paper cup. The corresponding force responses are presented in Figures 11, 12, and 13, respectively. The PID parameters used for the Type B gripper were ($K_p = 2.4$), ($K_i = 2.4$), and ($K_d = 0.6$).

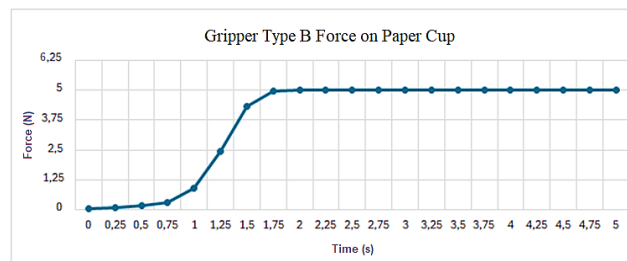


Figure 11. Response graph of gripper type B force on glass cup

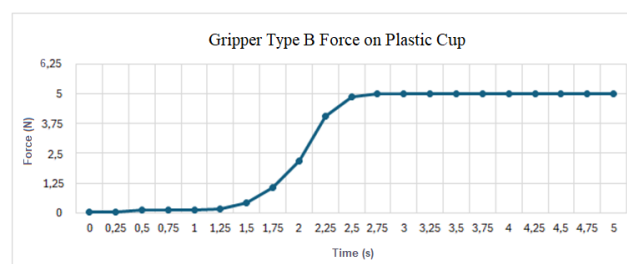


Figure 12. Response graph of gripper type B force on plastic cup

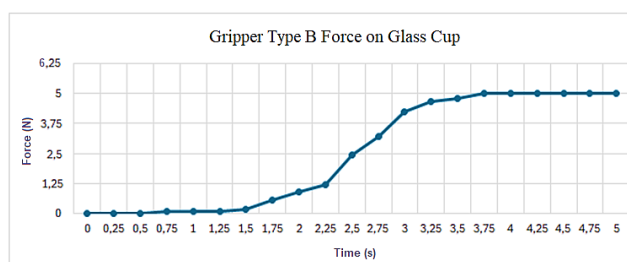


Figure 13. Response graph of gripper type B force on paper cup

Based on the force response graphs shown in Figures 11, 12, and 13, the Type B gripper was able to respond to changes in the applied force and approach the predetermined force setpoint. However, its response characteristics differed from those of the Type A gripper. In the glass cup test, the Type B gripper exhibited a relatively steady increase in gripping force and reached the desired force with a settling time of 2 seconds, although the response was slower than that of the Type A gripper. In the plastic cup test, the gripper showed a smoother response, with a settling time of 2.75 seconds. The paper cup produced the longest settling time of 3.75 seconds. Overall, the Type B gripper demonstrated a stable and relatively smooth force response across the three tested objects, and although it had longer settling times than the Type A gripper.

4. CONCLUSION

This research presents the design and implementation of an adaptive grasp force control system for a robotic gripper using a force-sensitive resistor (FSR) sensor and a PID control approach. The system was developed to enable the robotic hand to adaptively regulate its grip force when interacting with objects with varying surface characteristics. Experimental results showed that the FSR sensor provided force feedback with an average error of 0.112 N, indicating sufficient accuracy for gripping applications. The implementation of PID control tuned using the Ziegler–Nichols method successfully enabled the robotic gripper to achieve the desired force setpoint of 5 N. The Type A gripper demonstrated a faster response, with settling times of 1.75 seconds for a glass cup, 2.25 seconds for a plastic cup, and 3.25 seconds for a paper cup. The faster response observed with the glass cup was attributed to its rigid surface. However, the response became progressively slower when handling softer and more deformable materials, as deformation affected the transmission and detection of the applied force. In contrast, the Type B gripper exhibited longer settling times of 2.00 seconds for a glass cup, 2.75 seconds for a plastic cup, and 3.75 seconds for a paper cup. Overall, the proposed adaptive grasp force control system demonstrated its ability to regulate gripping force according to different object characteristics while reducing the risk of excessive force application. The comparison between the two gripper designs also demonstrates that the mechanical structure of the gripper plays an important role in determining force control performance and gripping behavior.

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