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Slip detection with accelerometer and tactile sensors in a robotic hand model

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Abstract. Grasp planning is an interesting issue in studies that dedicated efforts to investigate tactile sensors. This study investigated the physical force interaction between a tactile pressure sensor and a particular object. It also characterized object slipping during gripping operations and presented secure regripping of an object. Acceleration force was analyzed using an accelerometer sensor to establish a completely autonomous robotic hand model. An automatic feedback control system was applied to regrip the particular object when it commences to slip. Empirical findings were presented in consideration of the detection and subsequent control of the slippage situation. These findings revealed the correlation between the distance of the object slipping and the required force to regrip the object safely. This approach is similar to Hooke’s law formula.

1. Introduction
Human hands are an essential part of the human body. Tremendous structures have been created through human hands with precise capability. Human hands have an adequate ability to maneuver motions and accomplish complex actions (1,2). In addition, they consist of an array of hundreds receptive tactile sensors for sensory feedback mechanism. Thus, human hands can hold a particular object and automatically increase grasping force when the object begins to slip. Imperceptible changes can be easily detected through human skin sensibility. However, human hands still have some limitations in executing other tasks, such as dangerous or sophisticated operations in military and medical applications. In addition, high probability of errors can occur in repetitive and maintenance tasks because the capabilities of human hands have restrictions similar to limitations of other human abilities.

Thus, in recent years, significant efforts have been devoted to improve robotic manipulators, such as robotic hand or robotic claw. Currently, robotic hands begin as indispensable, especially because robotic hands have been broadly implemented in significant applications(3,4). In addition, robotic hand is widely used in automotive manufacturing industries for functions such as picking and placing, sorting, packaging, and palletizing, as well as in assembly and material handling production lines that require human hand substitution(5–7).

The most important issue in robotic hand applications is that robotic hands require distributed tactile pressure sensors that enable robotic hands to recognize the external environment. The primary emphasis placed on tactile sensors widely used in robotic hand applications is to measure the physical interaction that occurs through the contact points between the pressure sensor and a subjected object.
These tactile pressure sensors are designed and implemented based on different principle actions and materials, such as strain gauge, piezocapacitive, piezoelectric, pressure conductive rubber, and piezoresistive pressure sensors (8, 9). Researchers have focused on the comprehension of tactile sensor characteristics, and different useful illustrative applications have been performed in various fields (10).

2. Background study

Robotic hand is considered a mechatronic instrument that can do some activities that are impossible for humans. Robotic hand is widely used in manufacturing and dangerous nuclear industries, as well as in precise applications such as military or medical implementations. In addition, repetitive and maintenance tasks could be achieved with high performance accuracy. Consequently, evolving robotic hand is required to cover a wide range of tasks and to provide robotic hand with special types of sensors that can measure the grasping force for a particular object. Grasping objects could be achieved using the dexterous robotic hand presented in Ref. (11) which is illustrated with the ability to grasp both soft and hard objects. In Ref (12), gripping operation has been implemented by robotic hands that use special types of tactile sensors, which employ physical properties and events through contact with objects. Many tactile sensors have been developed, and the sensor hardware has evolved to achieve certain gripping tasks. Moreover, to accomplish the gripping mechanism using robotic hand, some efforts have been expended in developing tactile pressure sensor structures, such as in Ref (13). In most recent studies, advanced robotic manipulations have used tactile pressure sensors implemented in different applications. The main interesting issue in advanced robotic manipulation tasks is that robotic hand is required to be equipped with distributed tactile pressure sensors that can continuously provide information about the magnitude and direction of forces at all contact points between the sensing area and a subjected object. Numerous studies have reported the proposed method that uses tactile sensor information through physical contact between the sensor and an object to detect both pressure force and hardness of the object (14). In addition, several studies have documented that tactile pressure sensors have been utilized successfully in different design concepts and action principles. These tactile sensors have presented the process of determining physical features with the environment (15), measuring applied forces exerted over an object and the art in tactile sensing and investigating trends (16).

The well-known piezoresistive tactile pressure sensor (force-sensing resistor) (FSR) has been broadly used in robotic gripping implementations, such as gripping an object with different weights and shapes (17, 18). A pressure sensor indicates touch situation or continuous pressure force that occurs between the subjected object and the sensor. This indication depends on sensor resistance changes that correspond to the applied force. Thus, using a piezoresistive pressure sensor is appropriate in robotic hands for gripping operations. However, FSR does not provide information on slipping of a particular object. Thus, the proposed robotic hand model that uses FSR remains to have some defects in gripping operation. In the other words, FSR does not provide information on slipping that may occur during grasping implementations. In this study, FSR was developed to realize the algorithm of regripping an object after a slip situation has been detected. Subsequently, object gripping operation without slip situation detection is not adequately reliable, and objects may not be gripped perfectly. The evidence presented thus far supports the significance of slip detection. Thus, slipping motions in different orientations can be detected with accelerometer sensors that can measure tilt, vibrations, and acceleration force under gravity. An accurate motion of this sensor generates an acceleration signal on the basis of the principle of action and concept of design of that accelerometer sensor. Accelerometer devices based on acceleration forces were used in robotic applications to detect slip information (19–21). These accelerometers were protected by a foam layer to lessen noise effect. The system design in (22) includes two accelerometers: one of which is located at the contact point, and the other is situated far from the peripheral frame. The control system of this method calculates the difference between these two accelerometer sensors. In this study, the main objectives of using an accelerometer sensor are to
detect the acceleration signal caused by force gravity and to provide a control algorithm that deters slip continuity. Further data analysis was applied to investigate the features of the slipping signal, such as distance and velocity. Thus, the control feedback mechanism should accomplish the regripping algorithm that utilizes the slip distance signal to determine the required regripping force. This approach is presented with Hooke’s law, which estimates the required force for object regripping on the basis of its slipping distance. In this study, a completely autonomous robotic hand model that can detect whether or not an object exists in between robotic hand claws was designed and implemented. To achieve this purpose, an infrared (IR) sensor was used to provide an automatic gripping operation.

3. EXPERIMENTAL SETUP

3.1 Proposed robotic hand model

This study focused on designing and implementing the proposed robotic hand model for gripping an object with different weights. This robotic hand can detect a slip situation and can control the consequences of this situation. As shown in Figure (1), the simplicity and uncomplicated traits of the robotic hand model are its key features. Furthermore, the researcher designed and implemented a printed circuit board (PCB) to fulfill the purposes of the empirical study. The crucial aim of this research was sufficiently achieved.

![Figure (1) proposed robotic hand model](image)

Where 1 denotes PCB, MCU, and power supply; 2 denotes IR sensor; 3 denotes pressure sensors; 4 denotes DC servo motor; and 5 denotes the proposed robotic hand structure. Figure (2) illustrates that the accelerometer sensor is attached on the lateral part of the subjected object. The proposed robotic claws can be automatically closed after declaring that the object is
inserted between the robotic claws. The placed IR sensor indicates when the object is ready to be gripped. The subjected object was gripped with respect to the control feedback mechanism that was measured from the signals of acceleration response and tactile pressure sensors.

![Figure (2) accelerometer sensor has been attached on object](image)

The selected microcontroller unit (MCU) is Arduino Uno R3. This MCU has been chosen with respect to the following purposes: analog-to-digital converter, motor driver, pulse width modulation signals, digital in/out pins, analog input pins, low cost, and excellent compatibility with external components. The integrated circuit that has been implemented in MCU is an ATmega328. Moreover, the PCB in this study has been designed and implemented utilizing electronic components with high-quality performance and low power cost. As shown in Figure (1), these circuits are used to obtain experimental works that grip an object safely.

### 3.2 Schematic diagram of the experiment

In this study, the measured voltage of FSR can be specified through an analog readout circuit that was designed within PCB. Moreover, the output real-time data of the FSR and acceleration signal were displayed as graphs via LabVIEW application. Figure (3) illustrates the schematic of data extraction and signal processing. Further data analysis was conducted to process the data and to obtain signal features, such as velocity and distance. These features were provided after a double integral signal was applied to the acceleration signal, which was detected when the object slipped.

![Figure (3) schematic diagram of the experiment](image)

### 4. Results and discussion

Figure 4(b) illustrates that the gripping force dramatically decreased when the object started to slip. The voltage dropped to less than 0.2 V when the object slipped. This force denotes the output
measured voltage of pressure force sensors. The regripping force voltage increased again at the first attempt of regripping the object. The acceleration signal can be clearly observed in Figure 4(a). The control system for regripping the object after slipping was stimulated when the system utilized the acceleration signal as a feedback control signal. When the object was held, the measured output voltage was approximately linear and the acceleration signal was quiet. However, when the weight of the object was increased, the acceleration signal triggered the system to prevent slip continuity and regrip the object safely.

![Figure 4 (a)](image1.png)

![Figure 4 (b)](image2.png)

Figure 4 (a) and Figure 4 (b) show the signal response from accelerometer and pressure sensor during an object slipping.

After acceleration signal detection, the extracted data were analyzed to calculate slippage features, such as distance and velocity. These features were obtained by applying double integration to the acceleration signal. Figure 5 illustrates that an acceleration signal was generated when the object commenced to slip. At this point, the system was informed by the acceleration signal that triggers the system to regrip the object. This control feedback mechanism utilized the measured signal of the acceleration response after being analyzed.
Figure (5) demonstrates the velocity of the slipping situation and distance. On the basis of the experimental results, the automatic control algorithm was developed by utilizing the feedback mechanism. This approach is presented in Hooke’s law in Equation (1).

\[ F = K \times X \]  

(1)

Where \( F \) is force, \( K \) is a constant, and \( X \) is the distance of an object slipping that is used to determine the amount of the required force to regrip the object after the slipping signal was measured. To calculate the required re-gripping force based on Hooke’s law, the values of the distance of an object slipping and \( K \) are required to be calculated in this equation. Consequently, \( K \) in Equation (1) was calculated by repeating the experiment 10 times with different weights to determine an appropriate value of \( K \).
Figure (6) force (top), distance (middle) and $K$ (bottom) values over ten attempts.

Figure (7) Statistics of force, distance, and $K$ values.

Figure (7) Statistics of force, distance, and $K$ values.
In data analysis, the required force when the robotic hand tried to regrip the object until the object being gripped was calculated, and the distance of object slipping was measured during the same regripping attempt. Figure (6) shows three plots that represent the force at the top, the distance at the middle, and the constant $K$ at the bottom. Additionally, simple statistical analysis was conducted to calculate further parameter related to the force, distance, and $K$ values. Figure (7) illustrates that the $K$ value ranged from 0.1103 to 0.0142 and that the average of $K$ was 0.0535. The standard deviation was calculated to be approximately 0.02, indicating the wide extent of the measured data.

5. Conclusion
Various types of tactile pressure sensors have been widely used for robotic grasping operations. In this study, a robotic hand was modeled by utilizing piezoresistive pressure sensors for gripping force purposes. Moreover, an effective accelerometer sensor was used to detect the acceleration signal under gravity. Further analysis was conducted to obtain slippage information, such as distance and velocity. The control feedback algorithm was achieved to provide an automatic regrip by applying Hooke’s law, which evaluates the required regripping force from the distance where the object slipped. Tests and findings from the proposed robotic hand model illustrated three phases of gripping approach, namely, when the object was initially held, when the object started to slip, and when regripping attempt was secure.

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