Grasping Force Compensation Using a Fingertip Mechanism with Contact Point Estimation

Kei MIKAMI¹, Kotaro TADANO²

¹ Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology
(4259 Nagatsuta-cho Midori-ku Yokohama 226-8503 Yokohama Kanagawa, Japan) mikami.k.ac@m.titech.ac.jp
² Institute of Innovative Research, Tokyo Institute of Technology
(4259 Nagatsuta-cho Midori-ku Yokohama 226-8503 Yokohama Kanagawa, Japan) tadano.k.aa@m.titech.ac.jp

Received December 30, 2021 / Accepted June 12, 2022

Research has been extensively conducted on achieving stable grasping with a robot hand. Scientists have analyzed the slip and contact conditions and the grasping force. However, fault tolerance is a significant concern because the robot hand is expected to come into frequent contact with objects when the tactile sensor is positioned at the fingertip. Sensors that combine a flexible surface, such as gel, with a camera are less durable. Therefore, this paper proposes a method for contact point estimation and slip detection that does not require a tactile sensor. This method involves the combination of a pneumatically driven parallel link finger module and a fingertip mechanism using a pneumatic cylinder. Pressure change of the pneumatic cylinder is used to estimate the position of the contact point of the objects, and slippage is detected from the change in contact position. There is no need to place the sensor on the fingertip in this method. Therefore, this method is expected to improve failure resistance and help realize a robot hand that can grip stably. The ability to estimate the contact point position and compensate the grasping force for the slip via the proposed finger mechanism is confirmed via experiments.

Keywords: Pneumatics, Robotics, Finger Mechanism, Slipping, Tactile sensor-less system

1. Introduction

In recent times, human-robot coexistence has been widely researched in environments such as factories, medical and service fields. Given the presence of robots in such environments, it is crucial to consider the performance and movement of the robot’s hand, which comes in contact with objects during the robot’s operation. The robot’s complicated movements and grasping forces should also be appropriately controlled. These aspects are actively being investigated. In the current industrial robot system, the robot’s functions are divided between grasping an object via the hand and manipulating it via the arm. If the robot operates while maintaining the object's orientation once it is grasped, the object should be positioned such that it can be easily picked up. This is possible in a structured environment, such as a factory in the manufacturing industry. However, this feat is challenging in an unstructured environment, such as in medical and agricultural fields. If the object can be manipulated, its orientation can be changed after it is picked up. This significantly increases the number of practical tasks that can be performed with the object in hand. Additionally, the object can be gripped and prevented from falling by compensating for the grasping force immediately when slipping occurs. The robot hand can be used to stably grip objects by measuring the slip and compensation for the grasping force even when their properties (shape, mass, coefficient of friction, etc.) are not constant. This can also be achieved when an external force is applied to the object due to a sudden stop in the movement of the arm during the transportation of the robot. Therefore, during the manipulation of an object in hand, it is essential to detect the points at which the object is in contact with the finger.

Some studies have used a contact sensor to detect the grasping state from contact surface information. In addition, other studies have been conducted to adjust the grasping force by detecting slip and contact states using a tactile sensor. Melchiorri proposed a method to control the grasping force by detecting the translational or rotational slip using a force/torque sensor with a strain gauge and distributed tactile sensor. However, these methods require the static friction coefficient to be known despite their usefulness. Maeno et al. proposed an elastic finger to detect the distribution using a strain gauge with a curved surface. They showed that any object with an unknown weight and friction coefficient could be lifted at any speed. These studies employed tactile sensors to detect slip.

However, fault tolerance is a key concern because the robot’s hand is expected to frequently contact objects when the tactile sensor is fixed at the fingertip. In addition, when many sensors and distributed tactile sensors are mounted on the robotic hand, issues concerning wiring processing and amplifier placement are presented. The higher the resolution, the longer it takes to acquire sensor information and process data, which becomes a constraint during the real-time control.

In this context, it is also possible to use vision to obtain non-contact slip and contact information, although processing speed depends on the frame rate of the camera. In addition, high resolution is required to detect minute displacements. Even when a high-speed camera is used, the placement of the camera becomes a problem because space is often restricted around the hand. Thus, a fixed camera may give rise to a camera blind spot. It is also often necessary for adjustments to be made each time, depending on the surrounding environment in terms of factors such as brightness. Sensors that combine a flexible surface, such as a gel, with a camera, have been studied, but they have disadvantages in terms of durability.

In this paper, we propose a tactile sensorless contact point
estimation and slip detection technique to address these drawbacks. To realize the proposed method, we also develop a fingertip mechanism using a pneumatic cylinder. When an external force is applied to the pneumatic cylinder with the compressed air supply valve closed, the internal pressure of the cylinder changes. The contact point can then be obtained using the grasping force from the finger module and variation in the internal pressure of the cylinder.

We proposed a pneumatically driven finger module\(^{11}\). The grasping force could be estimated without employing a force sensor by driving the five-bar link using two pneumatic cylinders. Hereafter, the two pneumatic cylinders are described as drive cylinders. Tactile sensorless contact point estimation and slip detection are possible through a combination of the finger module and fingertip mechanism. Since the proposed mechanism does not involve a tactile sensor, it has an advantage in terms of fault tolerance.

The remainder of this paper is organized as follows. In Section 2, an outline of the proposed fingertip mechanism and contact-point estimation method is presented. In Section 3, the control system of the fingertip mechanism and the finger module is explained. Section 4 presents the experimental results. Finally, Section 5 summarizes the study and presents concluding remarks.

2. Fingertip Mechanism for Contact Point Estimation

2.1 Overview

Fig. 1 shows the configuration of the developed fingertip mechanism and each variable thereof; and Fig. 2 shows the layout of the proposed fingertip mechanism with the finger module. The fingertip mechanism employs a pneumatic cylinder. The supply valve was opened, and the compressed air was sent to one of the air chambers through the tube. Subsequently, the supply valve was closed. The change in internal pressure within the pneumatic cylinder was measured using a pressure sensor. The other air chamber was opened under atmospheric pressure. The grasping force \(F_s\) is the vertical force on the grasping surface of the fingertip link. The state corresponding to \(F_s = 0\) N is defined as the initial state. The load applied to the pneumatic cylinder was changed when \(F_s\) and the position of the contact point were changed, followed by the cylinder length \(l_r\).

2.2 Contact Point Estimation Method

This section describes the proposed contact-point estimation method using a fingertip mechanism. The torque around the fingertip joint \(\theta_{otip}\) is represented by the following relationship:

\[
F_s \cdot l_r = F_s \cdot l_s \sin \theta
\]  

where \(l_r\) is the distance between the contact point at the object and \(\theta_{otip}\), \(F_s\) is the reaction force of the pneumatic cylinder, \(\theta\) is the angle between the pneumatic cylinder and fingertip link, and \(l_s\) is the distance between the base of the pneumatic cylinder and \(\theta_{otip}\) as shown in Fig. 1. \(F_s\) can be obtained as follows:

\[
F_s = P \cdot A
\]

Here, \(P\) is the internal pressure (gauge pressure) of the pneumatic cylinder and \(A\) is the area subjected to pressure. \(\theta\) can be obtained from the cosine theorem by using the following equation:

\[
\theta = \cos^{-1}\left(\frac{l_t^2 + l_r^2 - l_s^2}{2l_t l_r}\right)
\]

Here, \(l_t\) is the distance between the rod end of the pneumatic cylinder and \(\theta_{otip}\). Assuming an isothermal change, the estimated cylinder length \(\hat{l}_s\) can be obtained from the changes in the internal pressure and volume of the pneumatic cylinder according to Boyle’s law, as follows:

\[
\hat{l}_s = l_d - \frac{V_0 - V'}{A}
\]

\[
V' = \frac{P_0 + 101.325}{P + 101.325} V_0
\]

Here, \(V\) is the volume of the cylinder and pipeline, and \(P_0\), \(V_0\), and \(l_d\) are the internal pressure, volume, and length of the pneumatic cylinder under no load, respectively. On substitution of Eq. (2)-(5) into Eq. (1), the estimated value of \(\hat{l}_s\) is expressed as follows:

\[
\hat{l}_s = \frac{P A}{F_s} \sin \theta \left(\cos^{-1}\left(\frac{l_d - \left(\frac{P_0 + 101.35}{P + 101.35} \frac{V_0}{A} \right)^2 - l_t^2}{2l_t l_r}\right)\right)
\]

\(F_s\) is obtained from the external force \(F^\text{ext} = ([F_s \cdot \theta_{otip}]^2)\), as shown in Fig. 3, at the tip of the finger module and fingertip link angle \(\theta\), as follows:

\[
F_s = F^\text{ext}_s \sin \theta + F^\text{ext}_z \cos \theta
\]
\[ \theta \text{ can be obtained from the angle between the fingertip link and the cylinder base link } \varphi_s \text{ and the cylinder base link angle } \varphi_m. \]

\[ \varphi_s = \cos^{-1}\left( \frac{l_t^2 + l_r^2 - l_s^2}{2l_t l_r} \right) \]

\( \varphi_m \) was obtained via geometric calculations based on the cylinder rod positions of the pneumatically driven finger modules \( q_1 \) and \( q_2 \). As this calculation process does not require the consideration of parameters related to the properties of the object, it is useful even in an unstructured environment.

The external force \( F_{ext} \) can be measured directly using a force sensor; however, in the case of the finger module proposed herein, \( F_{ext} \) can be estimated from the differential pressure of the pneumatic cylinder, and a kinematic model without a force sensor is required. This approach can potentially reduce costs and improve fault tolerance. In this study, the estimated value \( \hat{F}_{ext} \), which is described later, was considered as the external force at the tip of the finger module.

### 2.3 Proposed Fingertip Mechanism

Fig. 4 shows the developed fingertip mechanism with a finger module. The total mass was 0.29 kg. This mechanism employed a pneumatic cylinder (SMC, CP2B4-5D). The drive cylinders of the finger module were low-friction pneumatic cylinders (SMC, CJ2XB16-30Z) that were controlled via a five-port pneumatic proportional valve (FESTO, MPYE-M5-B) with an operating band of approximately 100 Hz. A linear potentiometer was used to detect the position of the cylinder rod, and the intake and exhaust of the pneumatic cylinder were controlled by a pneumatic solenoid valve (SMC, VQZ312-5M1-C6). The supply pressure to the proportional valves was set to 500 kPa, and the initial supply pressure of the pneumatic cylinder to 100 kPa. A semiconductor pressure sensor (SMC, PSE540) was used to measure the pressure of each port and the pneumatic cylinder.

### 3. Structure of Control System

Fig. 5 shows a block diagram of the compliance control system of the finger module. It can be applied to a pneumatically driven surgery support robot that estimates and controls the external force without a force sensor as well as the proposed mechanism. The position of the fingertip joint \( X(= [x \ z]_T) \) is calculated from the cylinder rod position \( q(= [q_1 \ q_2]_T) \) and the forward kinematics. The reference force \( F_{ref} \) was generated from the position error of the tip and transformed into the reference driving force \( f_{ref} \) for each cylinder using the Jacobian \( J_a \). Moreover, \( f_{ref} \) was controlled using a PI controller with feedback driving force \( f \), calculated from the pressure difference in the cylinder. The control signal was sent to the pneumatic proportional valve, and the force was generated by charging compressed air into the actuator.

The compliance and adaptability of the robotic hand must be ensured to achieve stable grasping for a grasping task to be executed successfully. In this study, the method proposed by Tadano and Kawashima\(^{12}\) is adopted for the control system. This control system has been applied to pneumatically driven surgery robots that perform...
external force estimation and force control without force sensors, and is suitable for the proposed finger module.

The fingertip was designed according to the motion characteristics described in Eq. (9), where $B$ is the viscosity matrix and $K$ is the stiffness matrix.

$$F_{\text{est}} = \begin{bmatrix} F_{x\text{est}} \\ F_{y\text{est}} \end{bmatrix} = B \begin{bmatrix} \dot{x} \\ \dot{z} \end{bmatrix} + K \begin{bmatrix} x_{\text{cmd}} - x \\ z_{\text{cmd}} - z \end{bmatrix} \tag{9}$$

The finger module previously proposed has a small mechanical impedance and high back-drivability. It can be driven with a small $F_{\text{ref}}$ when there is no external force. When $F_{\text{est}}$ is applied, $F_{\text{ref}}$ is generally the value required to resist $F_{\text{est}}$, which can be used as the estimated external force $\hat{F}_{\text{ext}}$. If the mechanical impedance of the finger module is large and not negligible, the feedforward compensation for driving force is required.

If the mechanical impedance of the mechanism is large and not negligible, it must be compensated by feedforward. A control system is constructed to drive the developed finger module. An ADC board was used to capture the signals of the potentiometer and the pressure sensor. In addition, a voltage signal is given as input from the DAC board to the proportional valves. The control cycle was set to 1 ms.

4. Experimental Results and Discussion

4.1 Experiment for assessing maintenance of cylinder internal pressure

Accurate estimates cannot be obtained using the proposed method if an air leak is present. Therefore, it was necessary to confirm the airtightness of the experimental system. After the solenoid valve was closed under the internal pressure of the pneumatic cylinder, the cylinder rod was moved ten times within 60 s with a full stroke. Then, $l_s$ was measured using an attached potentiometer, as shown in Fig. 6.

Fig. 7 (a) shows the measured value of the internal cylinder pressure, and Fig. 7 (b) shows the measured value of $l_s$. The internal pressure was maintained at 100 kPa before and after the experiment. The amount of air leakage from the experimental system was deemed sufficiently small to be neglected. However, in practical cases, the internal pressure of the cylinder may gradually decrease when the cylinder is operated continuously for a long time. For example, in pick and place or passing object operation, a robotic hand does not hold the same object for a long time. There was a period when the robot was not in contact with the object during the work cycle. If the internal pressure can be held for approximately 60 s, the solenoid valve can be opened to restore the cylinder pressure when the fingertip is not in contact with the object.

4.2 Experiment for contact point estimation

As part of this study, we conducted an experiment to estimate the contact point using the developed fingertip mechanism and finger module. The object, an arc-shaped resin, was positioned on a linear stage to be moved horizontally. The displacement of the linear stage is measured using a potentiometer. An overview of the experimental setup is shown in Fig. 8. The experimental parameters are listed in Table 1.
After the fingertip link was pressed against the object, the linear stage moved to the left, as shown in Fig. 8. Fig. 9 (a) shows the internal pressure of the cylinder, and Fig. 9 (b) shows a comparison between the measured cylinder length $l_s$ (dotted line) and the estimated cylinder length $\hat{l}_s$ (solid line). The displacement of the initial length of the pneumatic cylinder from 14.5 mm to 11 mm could be estimated from the pressure change.

Fig. 10 (a) shows the movement distance of the object measured using a potentiometer (Fig. 8). Fig. 10 (b) shows a comparison between the measured contact point $l_w$ ( Measured) and the estimated contact point $\hat{l}_w$ (Estimated). The measured contact point $l_w$ was obtained via geometric calculations based on the moving distance of the linear stage, cylinder length, and fingertip joint position obtained from each potentiometer. The estimated contact point $\hat{l}_w$ was obtained using Eq. (6). The error between the measured and estimated values was approximately 3 mm or less, which was reasonable. Since the estimated cylinder length agreed adequately with the measured value, the estimated grasping force used in the estimation calculation was assumed to be the cause of the error. Although there were improvements in grasping force estimation, changes in the contact position could be detected. Therefore, the estimated contact position can be used for slip detection.

In the case of slip detection, it was assumed that slip could be suppressed by compensating for $F_g$ proportionally to the amount of fluctuation of $l_w$ from the no-load state. The grasping force can be appropriately compensated by calculating the compensation force based on the amount of fluctuation $\Delta l_w$ even if there is an error in the absolute value of $l_w$. The static friction and hysteresis of the mechanism were determined to be the main factors affecting the error in grasping force estimation. Ultimately, the error in $l_w$ can be minimized by improving the accuracy of the friction model.

4.3 Experiment for grasping force compensation

The robotic hand is composed of the developed fingertip mechanisms arranged in opposite directions, as shown in Fig. 11. After grasping the object, the object slid in the direction of the arrow in Fig. 12. The grasping force was increased according to the total amount of slip estimated by the left and right fingers, as follows:

$$F_{g\text{cmp}} = K_g(\Delta l_{gL} + \Delta l_{gR})$$

(10)

$F_{g\text{cmp}}$ is the value of the grasping force compensation. $K_g$ is the gain in the grasping force compensation. $\Delta l_{gL}$ and $\Delta l_{gR}$ are the differences in the estimated contact point positions from the set points of the left and right fingers, respectively. The set point was the time at which the grasp was completed. To compensate for the grasping force, decompose $F_{g\text{cmp}}$ into the x- and z-axis components according to $\theta$, and add them to $F_{g\text{ref}}$ of the left and right fingers, respectively.

The grasping force and estimated contact point are shown in Fig. 13. $F_{gL}$ and $F_{gR}$ are the grasping forces of the left and right fingers.
respectively. In Fig. 13, the time at which the grasp was completed was set to 0s. As the contact point of the object changed from 0s to 3s, the total values of $\Delta \hat{w}_L$ and $\Delta \hat{w}_R$, that is, the estimated amount of slip, became 8 mm. It can be observed that $F_{gcmp}$ increases with a change in the amount of slip. This result confirms that the robotic hand with the proposed fingertip mechanism can change the grasping force according to the amount of slip.

The actual $l_{wl}$ and $l_{wR}$ were approximately 30 mm at the end of the experiment, so there was an error in the absolute values. The error is larger than the result in section 4.2. It may be due to the accumulation of errors in the estimated external force caused by the hysteresis of friction and posture of fingers when grasping. However, to compensate for the grasping force by detecting slippage, the relative change from the time when the grasping is completed is not a problem. Since the error is too large to estimate the grasping state from the contact point position in hand, further improvement in the accuracy is necessary.

5. Conclusion

In this study, we propose a finger mechanism that employs a pneumatic cylinder for contact point estimation. It was experimentally confirmed that the proposed finger mechanism could yield an estimate of the position of the contact point without the requirement of a tactile sensor. We also experimentally confirmed that the change in the estimated contact point position could be used to detect slippage and compensate for the grasping force. Furthermore, a low-cost robotic hand with excellent fault resistance can be realized by combining the proposed finger mechanism with the finger module that we developed. Overall, the proposed finger mechanism is an elemental technology prototype of a robotic hand, whereby stable grasping can be achieved.

In the future, we plan to improve the estimation accuracy of the contact-point position and apply it to in-hand manipulation. We also plan to conduct a functional evaluation of a multi-fingered hand with more than three fingers using the proposed finger mechanism.

References

1) Kawasaki, T. et al.: Dexterous Anthropomorphic Robot Hand with Distributed Tactile Sensor: Gifu Hand II, IEEE/ASME Transactions on Mechatronics, Vol. 7, No. 3, pp. 296-303 (2002)
2) Mizoguchi, Y. et al.: Development of Intelligent Robot Hand Using Proximity, Contact and Slip Sensing, Transactions of the Society of Instrument and Control Engineers, Vol. 46, No. 10, pp. 632-640 (2010) (in Japanese)
3) Melchiorri, C. et al.: Slip Detection and Control Using Tactile and Force Sensors, IEEE/ASME Transaction on Mechatronics, Vol. 5, No. 3, pp. 235-243 (2000)
4) Maeno, T. et al.: Control of Grasping Force by Detecting Stick/Slip Distribution at the Curved Surface of Elastic Finger, Proceedings of IEEE International Conference on Robotics and Automation, pp. 3896-3901 (2000)
5) Yamada, D. et al.: Artificial Finger Skin having Ridges and Distributed Tactile Sensors used for Grasp Force Control, Journal of Robotics and Mechatronics, Vol. 14, No. 2, pp. 140-146 (2002)
6) Maeno, T. et al.: Grip Force Control by Detecting the Internal Strain Distribution Inside the Elastic Finger Having Curved Surface, Transactions of JSME C, Vol. 64, No. 620, pp. 1258-1265 (1998) (in Japanese)
7) Ikeda, Y. et al.: Grip Force Control for an Elastic Finger Using Vision-Based Incipient Slip Feedback, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 810-815 (2004)
8) Ikeda, A. et al.: Grip Force Control of the Elastic Body based on Contact Surface Eccentricity During the Incipient Slip, Journal of Robotics Society of Japan Vol. 23, No. 3, pp. 337-343 (2005 (in Japanese)
9) Yamaguchi, A. et al.: Combining Finger Vision and Optical Tactile Sensing: Reducing and Handling Errors While Cutting Vegetables. The 16th IEEE-RAS International Conference on Humanoid Robots, pp. 1045-1051 (2016)
10) Li, R. et al.: Localization and Manipulation of Small Parts Using GelSight Tactile Sensing. Proceedings of the 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3988-3993 (2014)
11) Mikami, K. et al.: High Performance Finger Module for Robot Hands with Pneumatic Cylinder and Parallel Link Mechanism, Advanced Robotics, Vol. 35, pp. 1513-1524 (2021)
12) Tadano, K. et al.: Development of a Master Slave Manipulator with Force Display using Pneumatic Servo System for Laparoscopic Surgery, Proceedings of 2007 IEEE International Conference on Robotics and Automation, pp. 10-14 (2007)