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Control of Grasping Force by Detecting Stick/Slip Distribution at the Curved Surface of an Elastic Finger

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Abstract

A method for controlling the grasping force when an object is grasped by artificial elastic fingers is proposed. First, the relationship between the stick area and the internal strain distribution of the finger is calculated using FE (finite element) analysis. Based on this relationship, a method is proposed for controlling the grasping force by decreasing the increasing ratio of the tangential force when the stick area is decreasing. Finally, the grasping force is controlled using an actual elastic finger, which is made of silicone rubber and in which strain gages are incorporated. It is confirmed that objects can be grasped using adequate grasping force without complete slippage, even when the weight and the friction coefficient of the objects are unknown.

1. Introduction

Human fingers allow an object to be lifted by an adequate grasping force and without slippage, even when the weight and friction coefficient of the object are unknown. However, the mechanisms are not clearly understood. Johansson [1],[2] showed that partial slippage between the fingers and an object is important for grasping the object with the fingers.

In the field of robotics, use of a robot hand to grip and lift an object of unknown weight is one of the most important problems. Several methods for lifting objects have been proposed. These methods are generally classified into three types. One method involves detecting micro-vibrations of a finger when the object starts to slip [3]-[5]. This method produces an incipient slippage, and is not adequate for precise positioning because the object moves slightly to the lifting direction. The second method involves direct measurement of the friction coefficient between the object and finger [6],[7]. This method is convenient because the friction corn between the finger and the object is obtained. However, the artificial finger becomes large. The third method involves detection of a partial incipient slippage between the finger and the object. This method is thought to be similar to what humans do. Partial slippage refers to the contact condition between two bodies in which part of the contact area slips while the other part sticks. Tremblay [8] and Canepa [9] investigated the partial incipient slip between finger and object. However, in these studies the relationship between the design of the finger and the location of partial slip was not considered. Maeno [10] showed that the shear strain distribution pattern inside an elastic finger indicates the stick/slip condition at the finger surface during precision grip. The curved surface of the finger, the shear strain distribution inside the finger and the stick/slip distribution at the contact interface were found to be related. Maeno [11] also proposed a sensor capable of detecting the strain distribution inside an elastic finger having a curved surface. The strain distribution is measured by strain gages incorporated in the elastic finger. The strain distribution was confirmed to be obtained by the sensor. However, the method for controlling the grasping force was not clarified. In the present study, a method is proposed for controlling grasping force using the strain distribution inside the elastic finger in relation to the stick/slip information at the surface of the elastic finger. The feasibility of the proposed method is confirmed by FE simulation and measurements.

2. Method for controlling grasping force

2.1 Grasping by human finger

Figures 1 and 2 show the relationship between normal force (grip force) F_n and tangential force (friction force) F_t when an object is lifted by the fingers. The normal and tangential forces increase simultaneously until they reach the point at which the object can be lifted. However, the route indicated by the black arrow in Fig. 2 is not known.

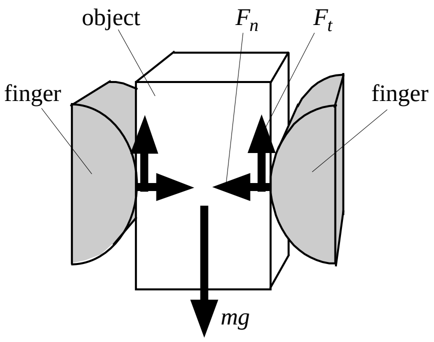

Fig. 1 Force between finger and object for grasping an object

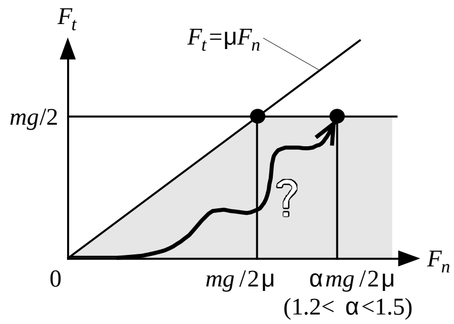

Fig. 2 Change in normal and tangential force for grasping an object

The problem of lifting an object without applying excessive force or producing a complete slip can be replaced by the problem in which the route and the destination point of the forces must be found.

How can the route and the destination point be found? Johansson [1], [2] measured the nerve signals and normal/tangential force simultaneously for human fingers gripping and lifting several kind of objects. The frequency of nerve signals was found to change when the friction coefficient between the finger and the object changes. The frequency of nerve signals also changes when the slope of the F_n-F_t curve in Fig. 2 changes. In addition, the normal force applied when the object is just lifted was shown to be 1.2 to 1.5 times larger than the minimally required normal force, $mg/2\mu$, for lifting the object. Information concerning the partial incipient slippage at the contact interface was reported to be necessary for the feedback control of the grasping force. The nerve signals may be carrying information about the partial slip for the feedback control. However, the quantitative relationship among the normal/tangential force, stick/slip condition, deformation/strain of the elastic finger and the nerve signals have not been clarified.

2.2 Relationship between stick/slip area and strain

In the present study, we analyze the contact between a finger having a curved surface and a plate in order to show that the change in shear strain is related to the stick area, rather than the partial slip area, and to propose a method for controlling grasping force using the above-mentioned information.

Figure 3 shows a cross section of a finger and an object. Since symmetry is assumed, only the right-hand finger is drawn. Figure 3 (a) shows the case in which only a normal force is applied. The finger deforms and the entire contact area sticks. Example rectangles are drawn near the contact surface. Figure 3 (b) shows the case in which a tangential force is also applied. There exists a stick area at the center of the contact and two slip areas at the edge of the contact. This occurs because the normal force distribution is semi-circular due to the curvature of the finger. Thus, the limiting friction force, the friction coefficient times the normal force, is small at the edge of the contact. When the tangential force is applied, the tangential reaction force, i.e. the friction force, reaches the limiting friction force near both edges of the contact. These areas then slip, kinetic friction force is applied, and the rectangular areas near the slip areas are no longer rhomboidal. In Fig. 3 (b), points 1-3 and 9-11 are slipping.

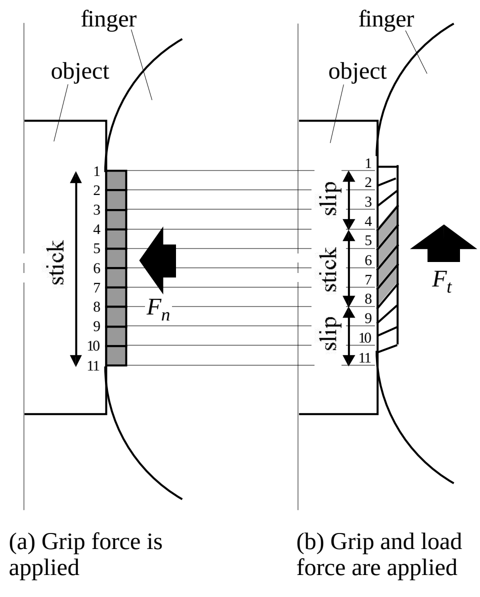

Fig. 3 Schematic view of the stick/slip distribution at the surface of the finger and the strain distribution inside the elastic finger

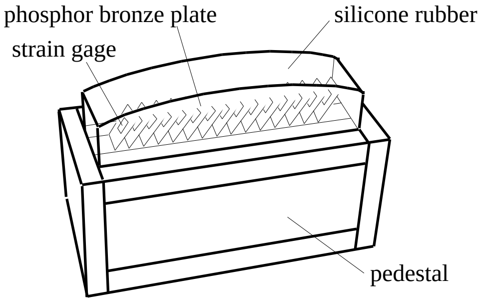

Fig. 4 Top view of finger-shaped sensor

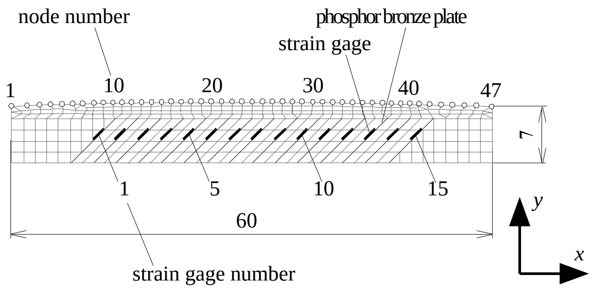

Fig. 5 Finite element model of the elastic finger

When the tangential force is increased, the partial slip areas increase from both edges of contact.

2.3 Proposed method

From the above discussion, the stick/slip condition can be estimated using the shape of the rectangular area, i.e. by the change in shear strain inside the finger near the surface over a short period of time. When the change in the shear strain at one point inside the finger reaches a certain value, then the surface near the point sticks. On the other hand, if the change in the shear strain at the point inside the finger does not reach this value, then the surface near the point slips.

Let us consider the situation in which an object is grasped. When the stick area is small, the normal force must be increased in order to prevent complete slippage. On the other hand, if the stick area is large, the tangential force must be increased, rather than increasing the normal force, in order to avoid crushing the object.

The following method is propose for controlling grasping force. The area of the stick region is monitored by the change in shear strain inside the elastic finger. The slope of the F_n-F_t curve is increased when the stick area is large and decreased when the stick area is small. This procedure is repeated until the F_n-F_t curve reaches the point, $(F_n, F_t)=(\alpha mg/2\mu, mg/2)$. The normal and tangential force are controlled without allowing complete slippage and without detecting the friction coefficient between the finger and object.

3. FE analysis of elastic finger

3.1 Calculation of fundamental case

In order to confirm that the proposed method is applicable for the sensor we produced in our previous study [11], FE (finite element) analysis is conducted for the case in which the normal/tangential force is increased. The contact problem that takes into account the stick/slip condition is solved by the method proposed in our previous study [11].

In the previous section, we showed that detection of the shear strain distribution inside the elastic finger is essential for controlling grasping force. Creating a sensor that is capable of detecting the shear strain distribution inside a homogeneous elastic body is difficult. However, in the elastic finger proposed in the previous study, normal strain is measured by strain gages within the elastic finger. The elastic finger is shown in Fig. 4. Fifteen phosphor bronze plates, each having a thickness of 0.1 mm, are incorporated at an angle of 45 degrees from the *x*-axis in an elastic body of silicone rubber. Strain gages are bonded to the phosphor bronze plates. The normal strain distribution pattern inside the finger has been shown to be similar to the shear strain distribution inside a homogeneous elastic body.

Figure 5 shows a plane strain FE model of the finger. This model was used to analyze the fundamental contact condition, including the stick/slip distribution, when the normal/tangential force is changed. The elastic modulus of the silicone rubber and phosphor bronze plate are 4.96 MPa and 1.35×10^5 MPa, respectively. Nodes at the bottom line are fixed. Plane strain elements are used. Nonlinearity

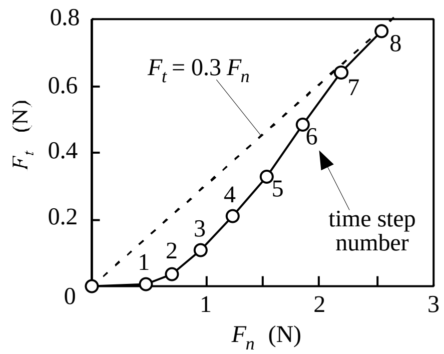

Fig. 6 Normal and tangential force calculated in FE analysis

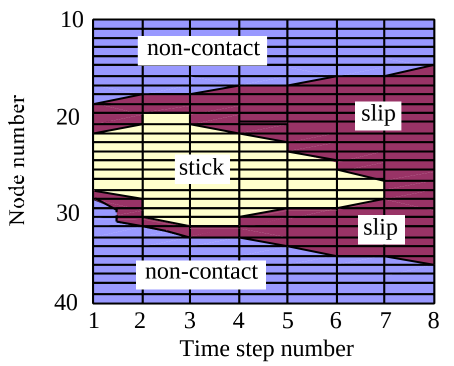

Fig. 7 Calculated contact condition

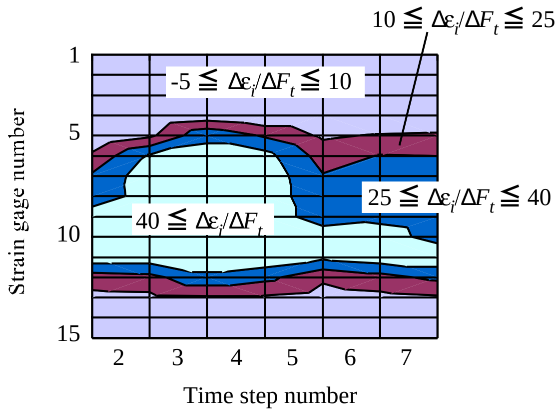

Fig. 8 Change in $\Delta\varepsilon_i/\Delta F_t$

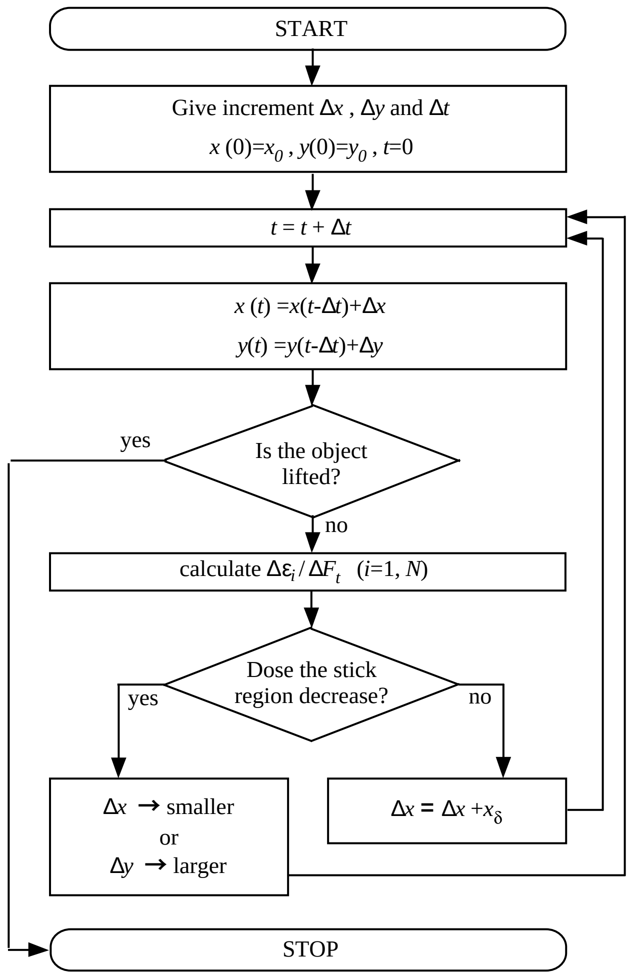

Fig. 9 Flow chart of proposed grasp force control by finger-shaped sensor

due to large deformation is neglected. Displacement of the plate in the normal/tangential direction is applied rather than the normal/tangential force, because the convergence of FE calculation is easier. Both procedures are equivalent. Figure 6 shows the change in normal/ tangential force for the fundamental calculation. Calculation is conducted for eight time steps.

The calculated contact condition is shown in Fig. 7. The non-contact area decreases as the normal force is increased. Stick area also decreases as the tangential force increases. Two partial incipient slip areas increase from the edges of the contact. Finally, at the eighth time step, the entire contact area slips. The phenomena is exactly as predicted in Section 2.2. In Section 2.2, we also predicted that the change in the strain distribution of the uniform elastic finger indicates the stick/slip information. Normal strain ε_i at the strain gages of the sensor indicates information that is similar to the shear strain in the uniform elastic finger. So the change in the normal strain of the strain gages per unit change in tangential force, $\Delta\varepsilon_i/\Delta F_t$, is calculated. Figure 8 shows the change in $\Delta\varepsilon_i/\Delta F_t$. The change in the area $40 \leqq \Delta\varepsilon_i/\Delta F_t$ is similar to that in the stick area. Both of these changes in area are large when the time step number is around three. After that, the stick area and the area where $\Delta\varepsilon_i/\Delta F_t$ is larger than 40 both decrease.

We also calculated the stick/slip condition and $\Delta\varepsilon_i/\Delta F_t$ for different friction coefficients. The relationship between the stick area and $\Delta\varepsilon_i/\Delta F_t$ was almost the same for all cases. Thus, we can conclude that $\Delta\varepsilon_i/\Delta F_t$ represents the area of the stick region at the surface of the finger independent of the friction coefficient.

3.2 Simulation of grasp

Control of grasping force is simulated using FE analysis in order to confirm that the proposed method can be used to control the normal/tangential force until the object is lifted.

A flow chart of the proposed method for controlling the grasping force is shown in Fig. 9. First, the initial values of Δ*x*, Δ*y*, *x*(*t*), *y*(*t*) and *t* are given, where, *x* and *y* represent the tangential and normal directions, respectively, and Δ*x* and Δ*y* represent the increments in the *x* and *y* directions, respectively. Then, the time *t* is increased by Δ*t* and the location of the finger is moved by Δ*x* and Δ*y*. The FE contact analysis is conducted for the given boundary condition. Next, we check to confirm that the object is lifted. If the object is lifted, grasping ends. If not, then $\Delta\varepsilon_i/\Delta F_t$ is calculated using the strain obtained by the strain gages. As mentioned earlier, $\Delta\varepsilon_i/\Delta F_t$ represents the area of the stick region. Thus, we check whether the stick region is expected to decrease. If the stick region decreases, the increment of *x* is made smaller or the increment of *y* is made larger in order to prevent complete slippage. Many procedures for decreasing Δ*x* or increasing Δ*y* can be used. In this case a simple procedure is selected for use in confirming the method. When the stick area decreases, Δ*x* is set to zero, which is equivalent to making the increment of the tangential force ΔF_t zero. If the stick region increases, the increment of *x* is set to x_δ so as to make the curve quadratic and prevent the object from being crushed. Then the time step is increased and the procedure is continued until the object is lifted.

Figure 10 shows the result of simulation for various friction coefficients. Dotted lines show the limit at which the object slips, i.e. $F_t=\mu F_n$. Let us look at the case of μ=0.3. When the F_n is equal to 1.5 and 4.7, the slope of F_t/F_n is set to zero because the stick region is decreased. Thus, complete slippage is prevented. In other cases, the normal and tangential forces are also controlled without complete slippage until the end of calculation. In other words, an object that is lighter than the last weight, $mg \leqq 2F_t$, can be lifted without slippage or the application of excessive normal force.

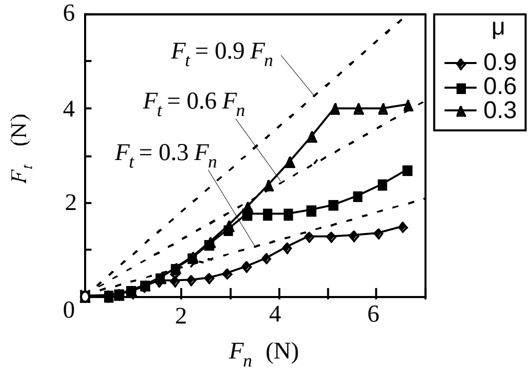

Fig. 10 Normal and tangential force calculated in FE analysis

4. Measurement

4.1 Equipment

The fundamental characteristics of the proposed sensor are measured in order to confirm that the control method can be used for an actual robot hand. Figure 11 shows the measurement system. The finger is connected to an *x-y* stage, the displacement of which is controlled by a personal computer. On the opposite side of the finger is a

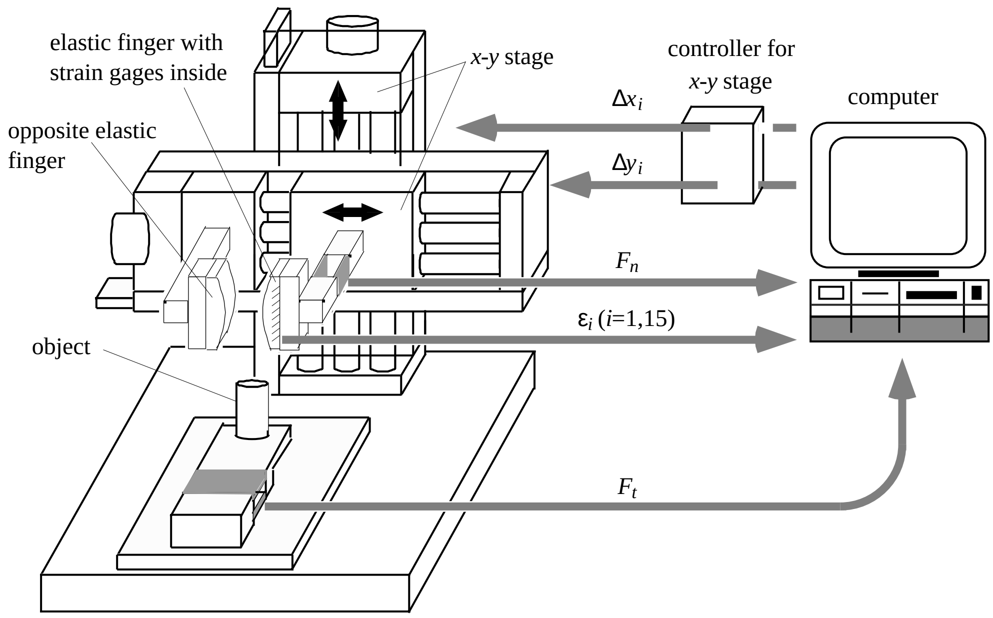

Fig. 11 Measurement system

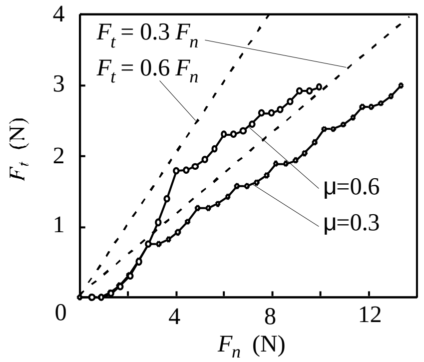

Fig. 12 Measured normal and tangential force

finger having the same geometry, but containing no strain gages. Strain ε_i of the fifteen strain gages inside the right-hand finger are measured. The normal and tangential forces are measured by strain gages bonded onto a phosphor bronze plate located in parallel at the robot arm and on the pedestal.

4.2 Measured results

Measurement is conducted according to the same procedure used in the FE simulation shown in Fig. 9. Figure 12 shows the measurements obtained for friction coefficients of 0.3 and 0.6. The dotted lines show the limit at which the object slips, i.e. $F_t=\mu F_n$. In both cases, the normal and tangential forces are controlled without complete slippage and without applying excessive normal force. The slope of F_t/F_n becomes zero several times in order to prevent complete slippage when the curve approaches the dotted line and the stick region decreases.

5. Conclusions

A method was proposed for controlling a grasping force using the strain distribution in relation to the stick/slip information at the surface of the elastic finger. The feasibility of the proposed method is confirmed by FE simulation and measurement.

The method is considered to be fundamentally the same as the grasping mechanism of human beings. However, the F_n-F_t curve, which is not continuous in the present study, is continuous in the case of the human finger [2]. The optimum condition for decreasing Δx or increasing Δy must be investigated in future studies. At present the hardware is complex due to the numerous sensors incorporated into the silicone rubber. Therefore, MEMS technology for producing small and multiple tactile sensors for detecting the shear strain distribution inside a curved finger should be further developed in future studies.

Acknowledgements

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