Vision Based Tactile Sensor Using Transparent Elastic Fingertip for Dexterous Handling

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1. Introduction

Humans have the ability to sense the weight and friction coefficient of the grasped object with their distributed tactile receptors. The ability makes it possible for humans to prevent from the slippage of manipulated object or collapsing the object. Such dexterous handlings are achieved by feeding back the signals from the receptors to muscle control system through neural networks. Therefore, it may be a key point for establishing dexterous handlings of robots when we try to mimic skilled human functions.
For tactile sensing of robots, several methods and sensors have been proposed by using electrical resistance, capacitance, electromagnetic component, piezoelectric component, ultrasonic component, optical component, and strain gauge (Shinoda, 2002), (Lee & Nicholls, 1999). There exist many problems of these sensors to be solved for establishing practical ones. For an example, the sensor which consists of elastic body and strain gauges requires a lot of gauges and the wiring. Moreover, the signal processing is not simple to obtain the values of the contact forces and the friction coefficients (Maeno et al, 1998). On the other hand, optical sensors have been introduced because wiring is not required in the contact part to the object (Ohka et al, 2004), (Ferrier & Brockett, 2000), (Kamiyama et al, 2003). The introduction of optical sensor makes the size small and the wiring simple. However, the sensing of friction coefficient is not considered in those papers. Piezoelectric sensors have a certain potential to solve the problems of size and wiring but there has not been a practical solution yet for measuring friction coefficient.
It is required for establishing dexterous handlings of robots to provide a purpose-built sensor for the measurement of friction coefficients between robot hand and the target surfaces. So as to avoid multiple usage of tactile sensors, we have proposed a new design of tactile sensors for multiple measuring of contact information including friction coefficient (Obinata et al, 2005).

2. Vision Based Tactile Sensor

We have proposed a vision-based sensor for multiple measuring of contact information including friction coefficient. The system consists of a CCD camera, LED lights, acrylic plate, and elastic body. The elastic body, which is made of transparent silicon rubber and has grid

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pattern or dotted pattern on the spherical surface as shown in Fig.2, is to contact the object. The CCD camera is to take pictures of the spherical surface from the flat surface side of the elastic body. The experimental setup is shown in Fig.3. We can apply not only arbitrary normal and tangential forces but also moments around normal axis of contact with the sliding mechanisms.

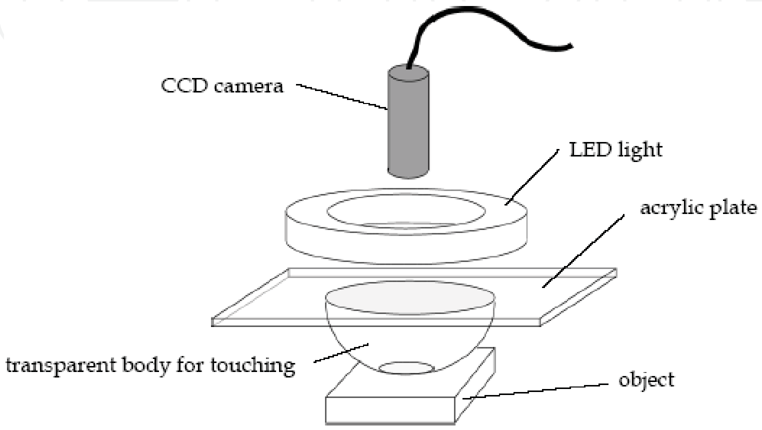


Fig. 1. Structure of vision-based tactile sensor.

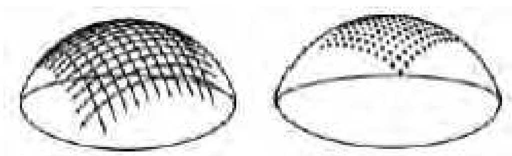


Fig. 2. Examples of shape and pattern on the surface of the elastic body.

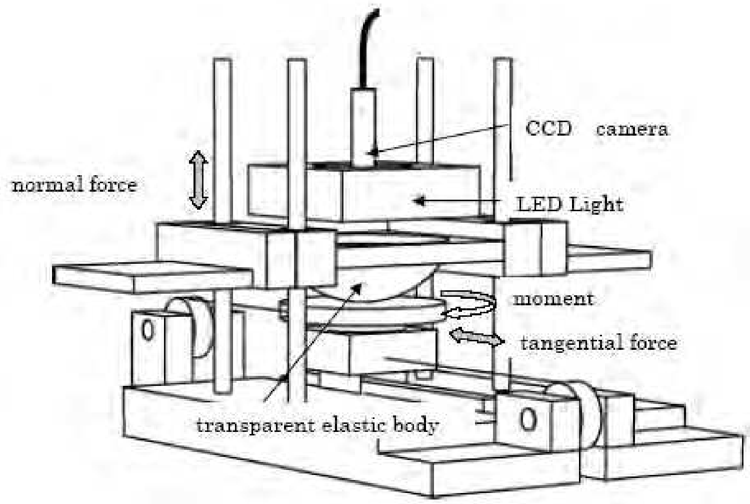


Fig. 3. Experimental setup for the sensor.

3. Measurement of Contact Force and Moment

3.1 Normal force

The relation between contact radius and normal contact force has been analyzed in cases of hemispherical surface (Xydas & Kao, 1999). The result provides the following relation:

$$a = cN^{\gamma} \tag{1}$$

where a is radius of contact area, c is a constant depending upon the material, γ is a constant depending upon the shape, N is normal force. This means that the normal force can be obtained from the contact area once the values of c and γ are determined. The picture of Fig.4 is an example when only a normal force is applied. We can estimate the contact area from the difference of brightness of each pixel; that is, we can obtain the estimation of the normal force. The dotted circle in the picture shows the estimated contact area with a certain threshold of the brightness. The experimental results are summarized as shown in Fig.5. The obtained values agree with the relation (1). The solid line in Fig.5 shows the curve with c = 4.35 and γ = 0.17. We can estimate normal contact forces based on this relation using the proposed sensor.

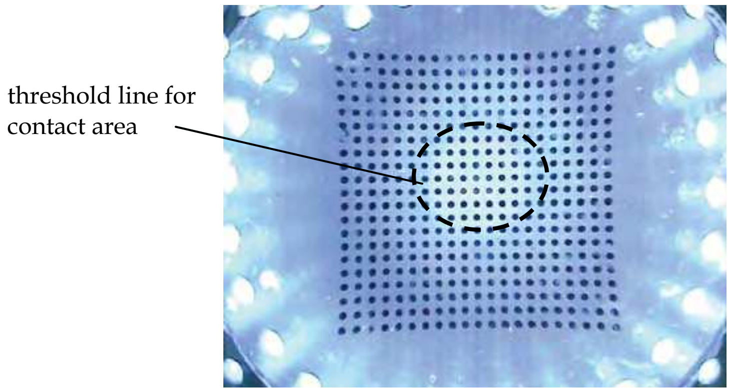


Fig. 4. Example of the picture (only a normal force is applied).

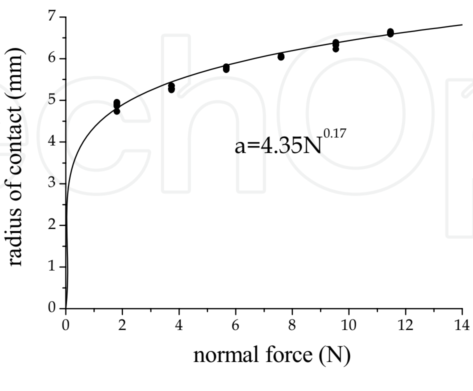


Fig. 5. Relation of radius of contact area to the applied normal force.

3.2 Tangential force

The picture in Fig.6 shows an example when normal and tangential forces are simultaneously applied. Central four dots on the surface of the elastic body were colored with red as shown in Fig.7, and are used as the origin and axes of the coordinate frame while identifying the displacements of all dots from the pre-contact positions. When the four dots are included in the contact area, the displacements of the four dots allow us to determine the direction of applied tangential force. We recognized that the displacements depend on the applied normal forces. On the other hand, the contact radius is independent on the tangential forces; thus, we estimate at first the normal force from the contact radius, and then estimate the tangential force with the estimated normal force. We found out the method for eliminating the dependency of

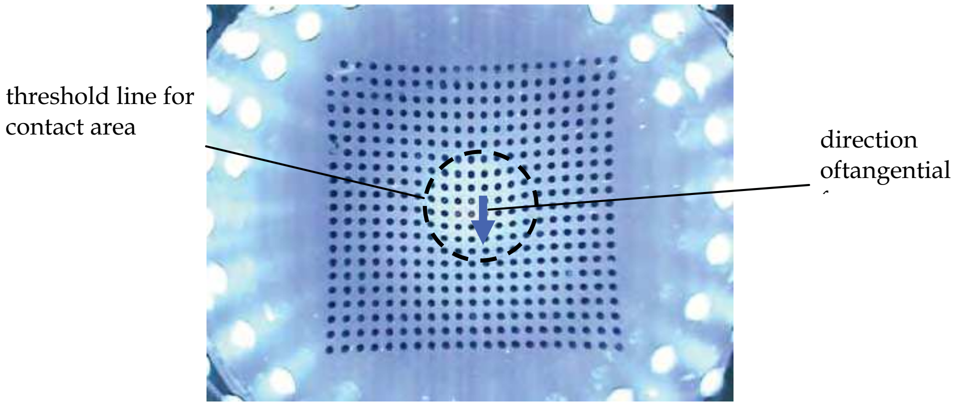


Fig. 6. Example of the picture.
(both normal and tangential forces are simultaneously applied).

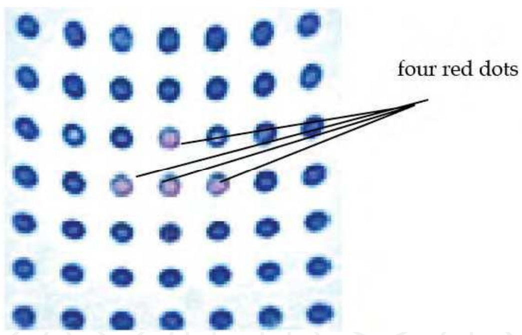


Fig. 7. Colored four dots on the surface of elastic body.

tangential force on the normal force by cut and try. Multiplying the ratio of contact radius to the measured displacements in tangential direction yields the normalized displacements. Then the relation between the normalized displacements and the tangential forces becomes one to one correspondence which is nearly expressed by one curve. The result of the normalization is summarized in Fig.8. Based on the relation, we can estimate the magnitudes of the applied tangential forces.

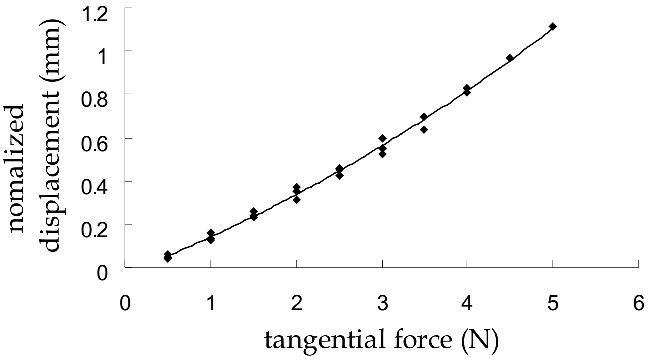


Fig. 8. Relation between normalized displacement and tangential force.

3.3 Moment

We can identify all dots on the surface of sensor in the coordinate frame defined by the colored dots. This fact allows us to obtain the vectors corresponding to the all dots which start from the positions of pre-contact phase and end at the positions of post-contact phase.

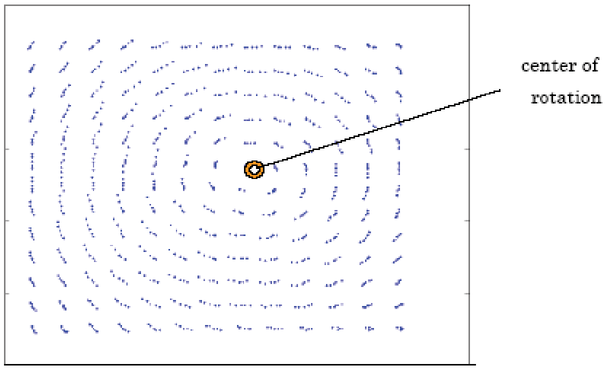


Fig. 9. Vectors for dots and center of rotation.

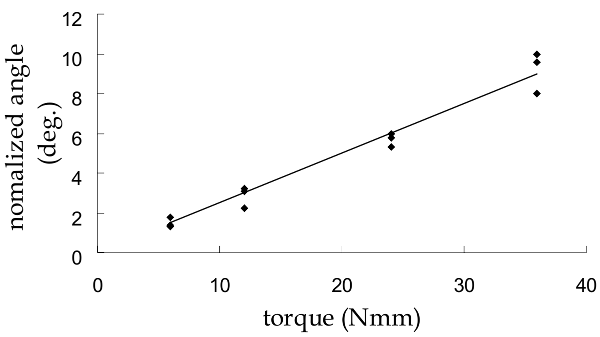


Fig.10. Relation between normalized rotation angle and applied moment.

We can estimate the center of rotation from the vectors when a moment is applied. Then, we can calculate the rotation angle from the position of the center and the vectors by using appropriate technique, for an example, least square method. The picture in Fig.9 shows how to estimate the center of rotation, for the example. We recognized that the estimated angles depend on the applied normal forces. We used the same method as the case of tangential force to eliminate the dependency; that is, the obtained angles were normalized by multiplying the ratio of contact radius. However, the result has a relatively large deviation and is summarized in Fig.10.

4. Estimation of Friction Coefficient

So as to prevent from the slippage of the manipulated object, we need to obtain the conditions of contact surface between the gripper and the object. The coefficient of static friction is important for handling the object without slipping. When the contact occurs between curved surface and flat surface, the pressure between the two surfaces distributes in the contact area. If the pressure of contact surface takes a lower value than the constant which is determined by both the surface conditions and the materials, the relative motion in tangential direction is possible in the area. This leads that the pressure distribution between the gripper and the object divides the contact area into two parts in general. In one part of contact surface, the relative motion in tangential

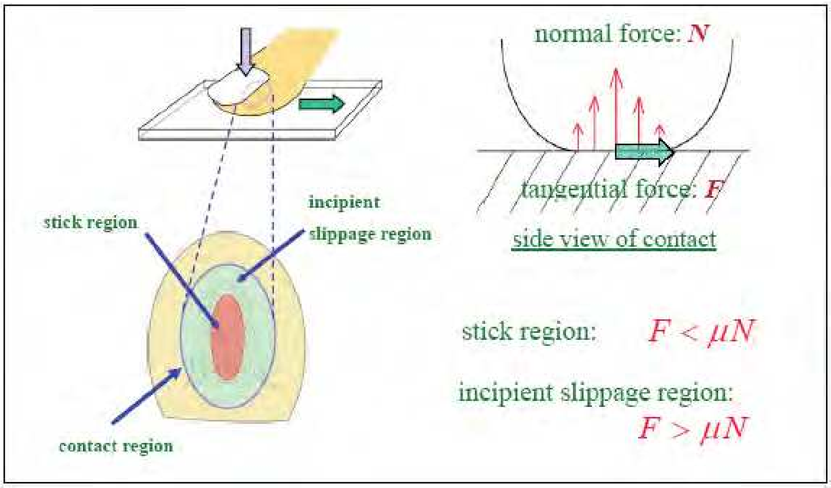


Fig.11 Schematic view of finger contact and definition of incipient slippage region.

direction is possible. We call the part as incipient slippage region. In the other part, the relative motion is impossible. This always occurs when human contact the object with fingertips. Several receptors in cutaneous sensory system of human distinguish these two areas. This means that human can sense the degree of slippage without macroscopic slippage occurring. The schematic view of finger contact and the definition of the two regions are illustrated in Fig.11. If we distinguish the two parts from the picture of CCD camera with our sensor, we can estimate the degree of slippage from the ratio of area of the incipient region to the total contact area. The ratio is defined by.

$$\rho = \frac{S_s}{S_c} = \frac{r_s^2}{r_c^2} \quad (2)$$

where S_s is stick area, S_c is contact area, r_s is radius of stick area, and r_c is radius of contact area. We call this ratio as stick ratio, and it relates to the friction coefficient. In the case of spherical and flat surfaces, the incipient slippage occurs in peripheral part of contact. So as to confirm the phenomenon experimentally with spherical and flat surfaces, we add a displacement sensor and a force sensor to the experimental setup of Fig.3. The force sensor measures directly the applied tangential force. The displacement sensor measures the movement of object. First, we identified the positions of all dots when only a normal force was applied. Next, we applied small additional force in tangential direction and increased the magnitude gradually. The dots in stick region moved in the direction, and the displacements were almost equivalent to that of the object. Note that macroscopic slippage did not occur at this moment while the surface in stick region moved with the object since the body of sensor is elastic. On the other hand, the dots in incipient slippage region moved a shorter distance in tangential direction because slippage occurred in the region. The relation between the initial distances of dots and the displacements for three cases of different tangential forces is shown in Fig.12. It should be noted that the radius of stick region decreased as the applied tangential force increased. When the radius reaches to zero, macroscopic slippage will occur. This leads to the possibility of estimating the degree of slippage from the displacements of central and peripheral dots. We propose a method for estimating stick ratio only from measurements of the sensor. The method uses the relative displacements of peripheral dots to the central dot. The radius of stick region can be determined by comparing the relative displacements with the threshold. In order to show the effectiveness of the proposed method, we carried out another experiments under different friction coefficients. We controlled the friction coefficient by using talcum powder on the contact surface and obtained the relation of the friction coefficients to the estimated stick ratios. The values of friction coefficient were determined with the ratio of the tangential force to the normal force at occurrence of the macroscopic slippage. We express the result with five lines in Fig.13. Each line corresponds to each friction coefficient. The lower stick ratio with the same displacement

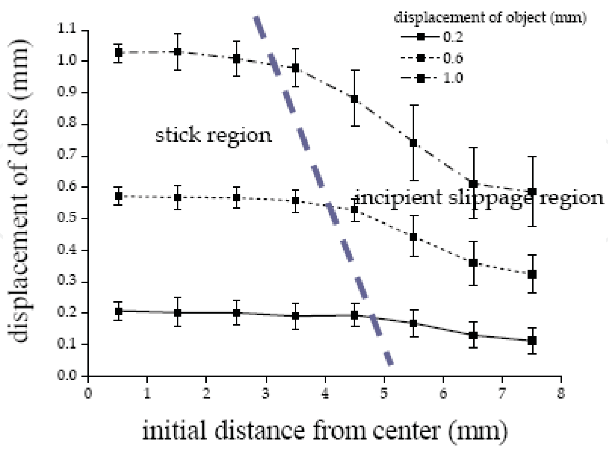


Fig. 12. Identifying incipient slippage region.

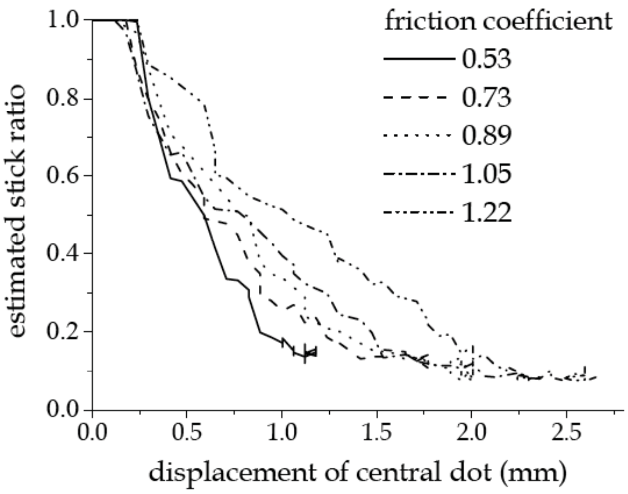


Fig.13. Estimated stick ratio in different friction coefficients.

of central dot means the lower friction coefficient. Although the proposed method cannot estimate smaller stick ratio under 0.1, we can use the estimated value to prevent from slippage because we can keep it over a certain value by feedback control of the contact force.

5. Control System for Robot Grippers Using Tactile Sensor

In this section, we describe the control system design for robot grippers to prevent from the slippage of the manipulated object. The feedback signal from the proposed tactile sensor is used to control the grip strength for stable handling of the object. The control system consists of the tactile sensor with image processing software, a voice coil motor, and a simple proportional controller with gain *K*, which is shown as the block diagram in Fig.14. The reference S_s^* is the set point for the stick area S_s. The controller amplifies the deviation $S_s^* - S_s$ by *K*, and transmit the calculated value to the voice coil motor. The voice coil motor generates the grip force under the control. The generated force is in proportion to the current in the voice coil motor. This feedback mechanism keeps the stick area around the set point. The experimental results of this control system are given by Fig.15. The tangential forces were applied manually; so, the curves in Fig.15 are not typical functions of time. The manipulated variables of control system correspond to curves in "current" of the second row which are in proportion to the generated normal forces. The current of one ampere is corresponding to the force of 3.5 N. The estimated stick ratios were normalized by the initial contact area and shows that a macroscopic slippage occurred while the control did not work. Moreover, it is shown in the figure that the control resulted in keeping the values of estimated stick ratio around the set point 0.5. This proves prevention from slippage by the control. It should be noted that the control system works only using signals from the tactile sensor.

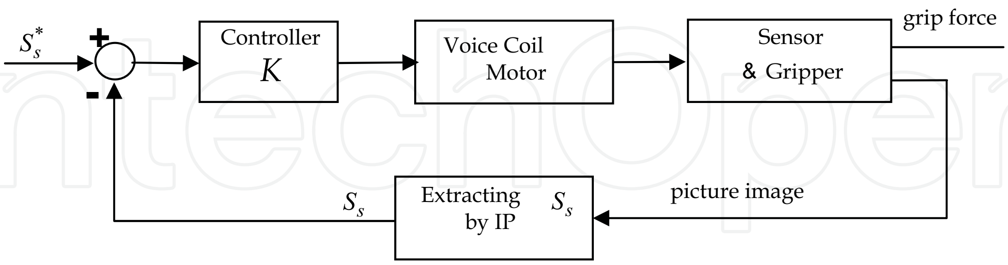


Fig.14. Block diagram of grip force control system.

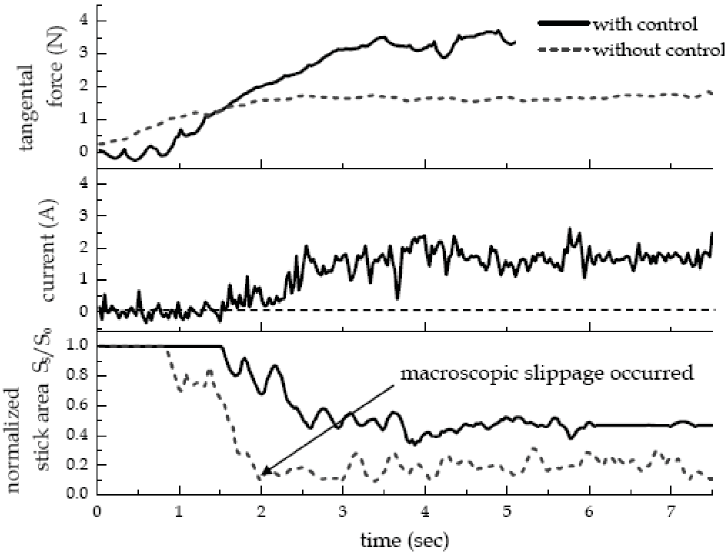


Fig. 15. Result of stick area control: Comparison between with and without control.

6. Comparison between the vision based sensor and a PVDF sensor

In this section a brief comparison is made between the proposed vision based tactile sensor and a fingertip shear force sensor made of poly-vinylidene fluoride (PVDF). Several earlier researchers have used thin piezo-electric films to sense the vibrations produced by object slip at the fingertip. However these sensors cannot measure the shear force that is essential for control of the fingertip normal force, and hence a new PVDF shear force sensor has been developed. The PVDF sensor works on the principle of directional properties of poled polymers. Poling is done with the application of a high DC voltage to orient the molecular dipoles in a particular direction. This causes the polymer to respond independently to forces in the three principle directions, as explained in (Furukawa, 1989). A small sensor was developed using poled PVDF of size 10 x 15 mm as shown in Fig. 16. The PVDF film is metallic coated on both sides on which thin wires are attached to collect the charge generated by the applied forces. The polymer film is placed in between two layers of rubber

(1 mm thick) and the whole composite assembly is placed on an aluminum 'finger' of thickness 5 mm. This prevents the polymer from bending. The three layers are bonded together by means of epoxy adhesive. Details of the polymer used are as follows:

material : PVDF, MONO
polarization class: 1-A
thickness : 25 micro-m
metallization : Ni, Cu both sides as electrode
dielectric constant : d31 ≠ d33 (where 3 refers to the poling direction)
E=3.5 Gpa

The sensor was placed on one finger (similar to Fig. 16) of a two-finger robot gripper and calibrated for different shear forces acting along the x-direction. Calibration result is as shown in Fig. 17. Several experiments were performed in which the sensor was used to grasp an object with a desired normal force and then a shear force was slowly applied to the object, to cause it to slip. Figure 18(a) shows that as the shear force increases it is recorded by the sensor. The shear force remains almost constant while slip occurs, until the object goes out of the grip. This same phenomenon is also shown in Fig. 18(b), where the shear force increase is recorded until slip occurs. Slip is recorded as a disturbance until the grip fails. From these figures it is not possible to accurately predict micro slip until macro slip takes place. Hence it is also not possible to take corrective control action to prevent macro slip. Other differences between the two sensors are, the signals obtained from PVDF sensor is noisy and requires signal processing and also measurement of a moment is not possible. The merit of the PVDF sensor appears to be its small size, weight and low cost. This comparison highlights the various advantages of the vision based tactile sensor over other types of piezo-sensors proposed so far.

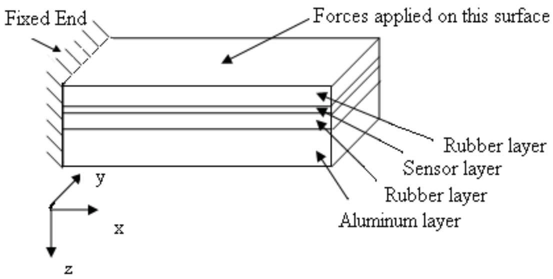


Fig. 16. Details of PVDF sensor attached to an aluminum finger.

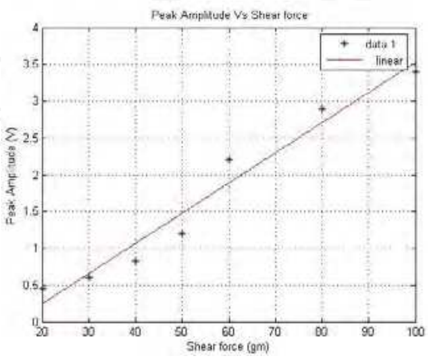
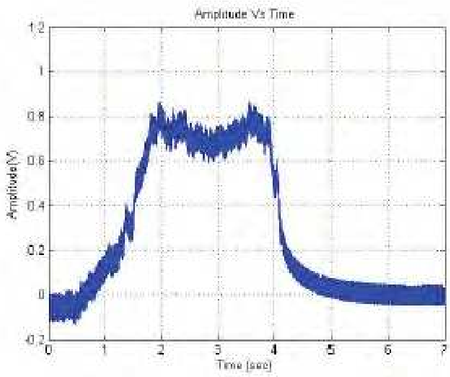
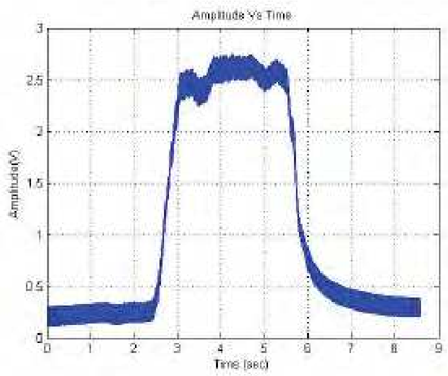


Fig. 17. Calibration of sensor output verses shear force on object.





(a) (b)

Fig. 18 (a) Shear force of 0.35 N applied to object (normal force 0.45 N),(b) shear force of 0.7 N applied to the object (normal force 0.9 N)

7. Conclusion

We have explained on a new tactile sensor for measuring multi-dimensional force and moment of contact. The structure of sensor is simple because the method is vision-based. The method to obtain the values of force and moment has been confirmed by several experiments. It is shown that the accurate estimation of contact force and moment is possible with the proposed sensor although there is a trade-off between the resolution and the computational time. There exist small interpositions between the tangential force, the moment and the normal force while measuring. Clear understanding the interposition between applied forces and moments will be required in further research. We defined the stick ratio as an index for indicating the degree of slippage. We have also proposed a new method to estimate the stick ratio for preventing from slippage of manipulated object. The exact relation of the defined stick ratio or the estimated stick ratio to the exact friction coefficient is an important problem to be solved. We demonstrated the control system for keeping the estimated stick ratio around a set point. Moreover, we have given a comparison with a piezoelectric sensor because it may be another candidate to cope with several practical requirements. The purpose-built integrated circuit for the image processing of this vision-based sensor may be required to achieve high speed control against disturbances in high frequency band. It is shown that the proposed sensor has the potential for dexterous handling like human.

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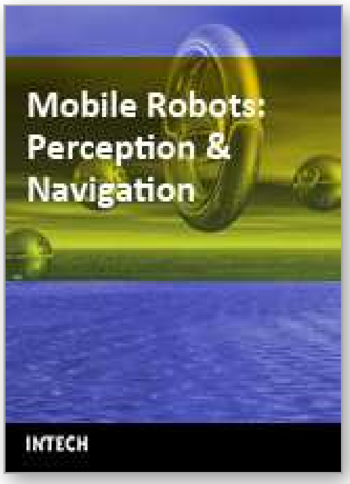

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Today robots navigate autonomously in office environments as well as outdoors. They show their ability to beside mechanical and electronic barriers in building mobile platforms, perceiving the environment and deciding on how to act in a given situation are crucial problems. In this book we focused on these two areas of mobile robotics, Perception and Navigation. This book gives a wide overview over different navigation techniques describing both navigation techniques dealing with local and control aspects of navigation as well es those handling global navigation aspects of a single robot and even for a group of robots.