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Active Tactile Sensor using Deformable Sheet Reflector

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Summary

Emphasizing the importance of active sensing schemes, we propose a new principle of tactile sensor which can detect a solid profile and a gradient profile of the surface with small movements or vibration of the sensor body. It utilizes a deformable reflecting layer as a contact medium, a back-lighted transparency as a light source, and a TV camera as a detecting device. All of them leads to very high resolution of the tactile information. A CCD camera inside the body catches the reflected light pattern modulated by a surface texture as an image. The image becomes a function of time because the sensor body is moving. From this function, we extract features of contacting object. We classified the possible movements of sensor by means of degrees of freedom. Then we formulated the available information from them. Through several experiments, we confirmed that by simple movements of the sensor body and by a simple temporal correlation calculus we can obtain shapes, surface normals, and edges of the contacting object.

Keywords: *tactile sensor, active, reflection, shape, edge, surface normal*

1 INTRODUCTION

There have been several attempts to adopt activeness to tactile sensor [1]-[5], but since most of them [1][3][4] used robotic manipulators, the "activeness" meant the big movement, bigger than the sensor. We now consider the small movement or vibration of the tactile sensor. It is because human utilizes such small movements to recognize local features of the object. For example, a voluntary touch itself is already a movement, because to feel something, one moves up and down one's finger vertically.

Our sensor system consists of: 1) a transparent elastomer as a sensor body, 2) illuminated transparency surrounding it as a light source, 3) deformable sheet reflector on the contacting surface, 4) a CCD camera to catch a pattern on the reflector, and 5) an actuator to move the sensor body.

We classify the movements according to the degrees of freedom of it. According to the classification, we consider the available information about the contacting surface and formulate the extraction algorithm for it. We describe a fabrication procedure of the sensor and the deformable sheet reflector. We show several experimental results to evaluate the performance of the sensor.

2 GENERAL IDEA OF ACTIVE TACTILE SENSOR

2.1 6-D Sensor Movement

What can we extract from small movement of the tactile sensor? In this section, we answer this question systematically. We classify the movement by degrees of freedom and discuss about each type of movements separately.

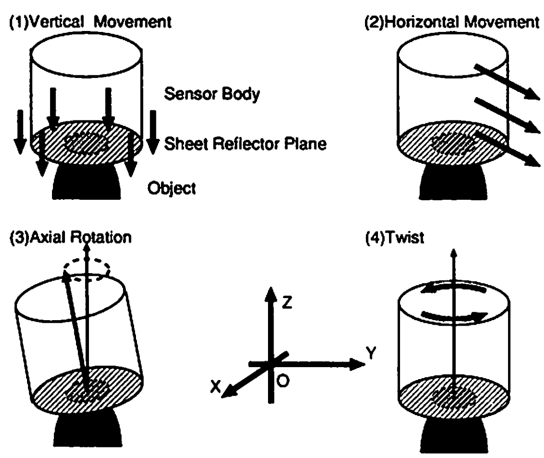


Figure 1. Four types of tactile sensor movement.

The sensor movement has 6 degrees of freedom (Figure 1.). Since a rotational origin of sensor and object around z axis is arbitrary, these 6 degrees can be classified into the following 4 types: 1) movement in the direction of z axis (vertical movement), 2) movement on $x-y$ plane (horizontal movement), 3) rotation around x and y axis (pitch and roll), and 4) rotation around z axis (yaw). The combination of pitch and roll makes the sensor move like the earth's axis (axial rotation). The rotation around z axis makes the sensor body twist. Therefore, we will call it a twist.

Friction makes the problem difficult. When the sensor is moved considerably, some part of the contacting surface slips but other part doesn't move because of the friction. These phenomena are quite unpredictable. In researches concerning big horizontal movement, the friction was neglected and the movement was used as an active spatial filter [2]. In other approaches, induced vibration caused by the friction was used to identify objects [5]. However, if movements are vertical movement or axial rotation, we need not consider the slip because the movement we consider is very small.

2.2 Sensor System

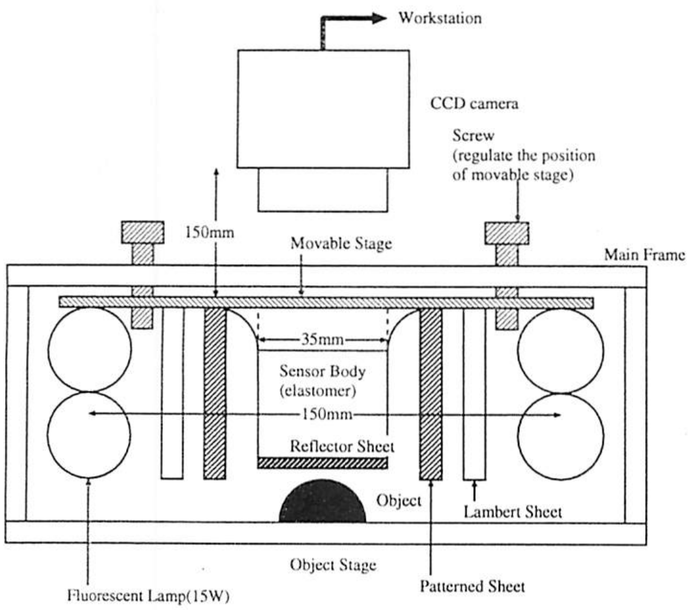


Figure 2. Sensor System.

Figure 2 shows our sensor system. The central part is a sensor body which is made of transparent silicone rubber (Shin-etsu Chemical, "KE-1935"). On the contacting surface of the sensor body, we attached a thin layer of reflector sheet which we will describe the detail in Section 2.3. Figure 3 is a photograph of the sensor body. It is 35mm in diameter and 40mm in height.

Around the sensor body, there are two circular luminescent lamps. Between the sensor body and the lamps, two superposed transparencies are placed. One is a Lambert sheet and the other is a patterned sheet. Lambert sheet (thin paper) makes the light spatially uniform. Patterned sheet has varying distribution of light transmittance. It is made of OHP (overhead projector) sheet printed a functional pattern with black ink. Light from lamps go through two transparencies and is reflected at the deformable reflector. We observe the reflected light through the sensor body by a CCD camera. The image sequence is sent to the workstation.

As shown in Section 2.3, we may consider the reflector sheet as a mirror. Therefore, what we observe is an image of the patterned transparency. If the reflector sheet is deformed by the contact, its inclination changes the path of light, which we observe as the change of CCD

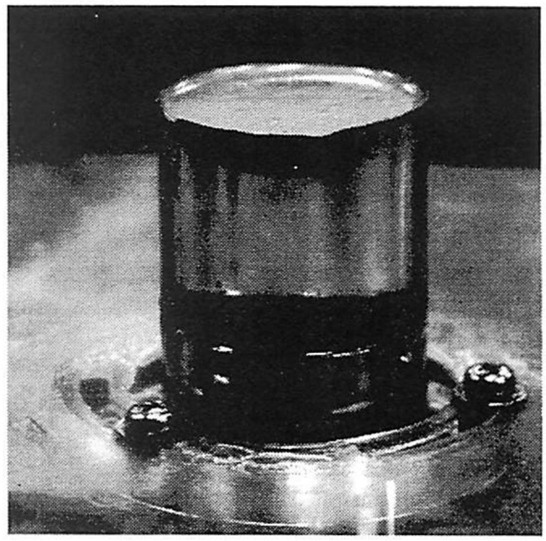


Figure 3. Photograph of the Sensor Body.

image. The sensor body, lamps, and transparencies are all attached on a movable stage, and the movable stage is connected to the main frame of the sensing system. We simulated the small movement of the sensor by moving the stage manually.

The point of this system is its softness. There have been a few attempts to utilize elastomer as sensor body. Fearing used it as a low pass filter[7], Shinoda and Ando used it as ultra-sound medium[8]-[11]. We now use it as light and contact medium.

2.3 Deformable Sheet Reflector

The reflector sheet is made with the silicone spray containing aluminum crystal powders (San-esu Engineering, "Mirror Coat"). The powders most of which have a shape like a thin plate work as mirror fragments. As they are coated with excess solvent at first, the crystals settle down before it is solidified, piling up parallelly and consisting mirror-like deformable sheet. Our observation showed that the maximum scattering angle of the reflected light is about 3 degrees. We consider that this scatterness works as a proper low pass filter.

In most sensing systems utilizing light reflection, the Lambertness of the object surface is desired. In our system, the condition is achieved by using a mirror reflector coupled with a planar light source. From this we can obtain several benefits as follows: 1) inclination-sensitivity is enhanced by the optical lever principle, 2) planar light source can be easily minitualized to make a finger size device, 3) planar (incoherent) light source can be flexible, and 4) we can add a brightness pattern easily to the distributed light source.

Maekawa [3] introduced first the optical transduction method to tactile sensors. He used an optical waveguide and an elastic cover. The thickness of the waveguide, the cover and the air gap between them determines the resolution, because the elastic cover as contact medium works as a spatial low pass filter[7] as well as the air gap which must have considerable thickness.

On the contrary, what is needed for our system is "boundary" to reflect light. Thus, the sheet reflector as a contact medium can be very thin (0.05mm), which leads to superior resolution. Although it is thin, it is not so weak. This is because the reflector is coated directly on the sensor body and both of them are made of the same material (silicone rubber). Therefore it is free from the stress concentration which become the main cause of destruction of elastomer.

3 RECONSTRUCTION OF SHAPE BY VERTICAL MOVEMENT

3.1 Principle

Vertical movement is the most basic movement for active tactile sensor. We show that by vertical movement 3-D profile of the object are obtained.

The extraction procedure is as follows. We lower the sensor body from a known position at a constant velocity. Let the velocity of the sensor be v, the time traveled from the position be t, deformation of the sheet reflector be $F(x,y,t)$, and shape of the object be $f(x,y)$. Under the assumption that the sheet reflector is thin enough to consider that the shape of an object is fully transfered to another side, $F(x,y,t)$ is described as

$$F(x,y,t) = f(x,y) \cdot H(-vt - f(x,y)) \tag{1}$$

where $H(z)$ is a unit step function.

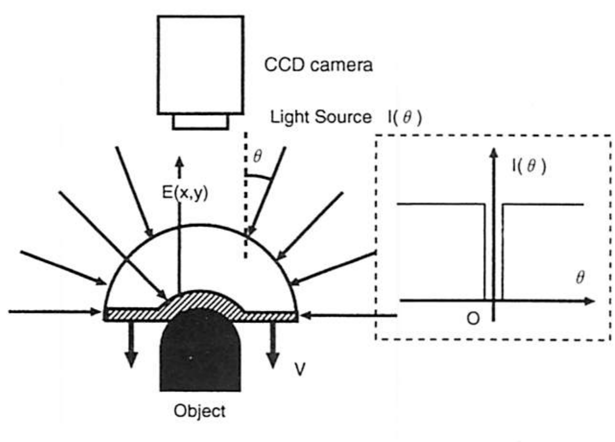


Figure 4. Function of light source in vertical movement.

Let the spatial distribution of the patterned transparency be uniform (Figure 4.). When the sheet reflector is flat (it is flat before touch), all the light pathes are outside the transparency, which means that no reflected light is observed (a dark state). If the sheet deforms and has an inclination larger than a threshold, reflected light from the transparency is observed (a light state).

Since areas contacting an inclined object or areas surrounding a contacting point have inclination, the light state indicates there are some contacts on or near there. Therefore we call a light state a contact state. From Eq.1, the condition for the light state for the point (x,y) is expressed as

$$-vt - f(x,y) \geq 0 \tag{2}$$

Therefore, if the brightness of the CCD image at (x,y) changes from a dark state to a light state at a time $t(x,y)$, we can place "a contact label" at this point and obtain a height information as

$$f(x,y) = -vt(x,y). \tag{3}$$

Namely, the vertical movement converts the height information (z axis) to time information (t axis). The above argument also shows that the height information for flat contacts or vertices of the object cannot be obtained. We will discuss this point in the next section.

3.2 Experiment and Evaluation

First, we measured the sphere, 10mm in diameter. We lowered the movable stage by 0.1mm a step and took the image. We repeated it 30 times from $n = 1, 2, \cdots, 30$. From these 30 sequential images, we detected the state changing time $n(x,y)$, and reconstructed the shape as

$$f(x,y) = -0.1n(x,y) \quad \text{[mm]}. \tag{4}$$

Figure 5(a) is the result of reconstruction. (b) shows a cross section of it. From them, we can state as follows:

- Most parts are reconstructed accurately. The main cause of inaccuracy is considered to be the flexure of movable stage.
- Where the inclination of object is nearly 0, the shape is not obtained. Since the height of the regions without a contact label (unknown region) is set to zero, the sphere looks like a crator.

For the second problem, however, the height of those unknown regions can be extrapolated by a proper software from surrounding heights. So we suppose that this is not a critical problem.

Second, to demonstrate the performance, we measured the 5 yen coin (22mm in diameter). The result is Figure 6. We represented the height by brightness.

We must emphasize that concave part is reconstructed as well as convex part. This is done by using incompressive (poison rate $\sigma \simeq 0.5$) elastomer as the sensor body and the sheet reflector.

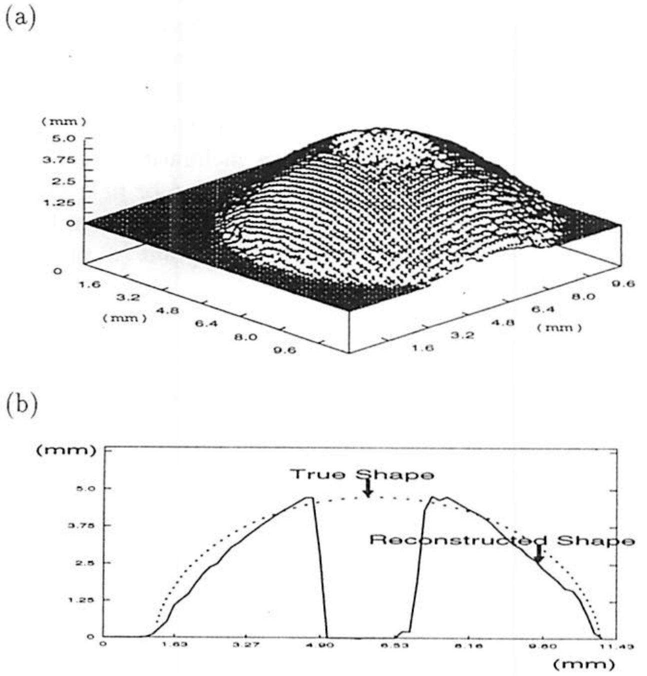


Figure 5. (a)Reconstruction of Spherical Object.(b)Cross Section of (a).

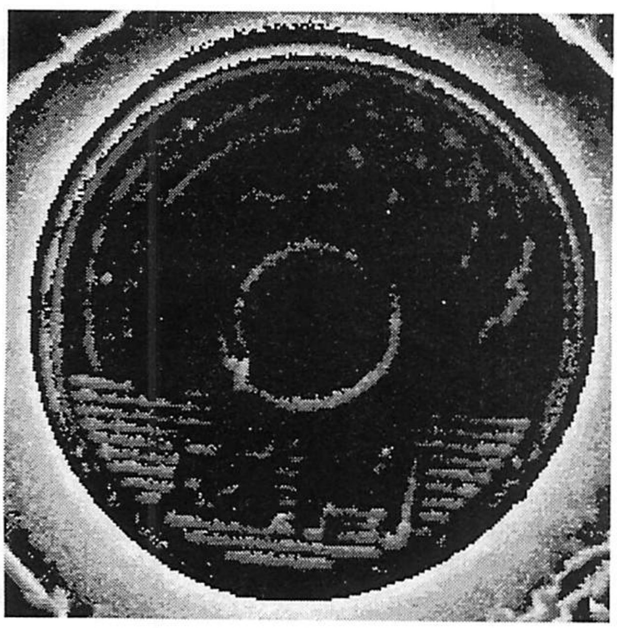


Figure 6. Reconstruction of 5 Yen Coin (22mm in Diameter).

4 DETERMINATION OF SURFACE NORMAL BY AXIAL ROTATION

4.1 Principle

In order to feel the shape of objects, one can't always move one's finger vertically, because he may be holding something which must not be dropped. Axial rotation is the proper movement under such circumstances.

We found out that by axial rotation, "normal" of contacting surface is determined by using temporal correlation.

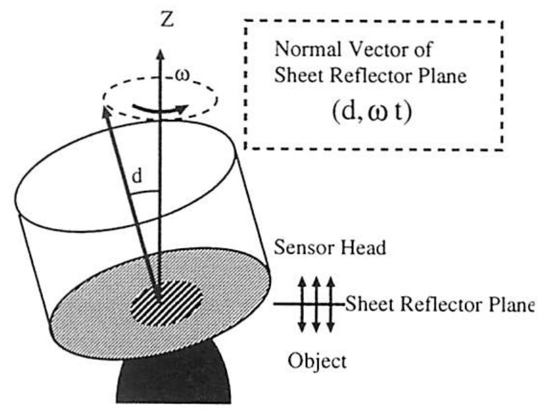


Figure 7. Axial Rotation.

The algorithm is as follows. Let the zenithal angle of sheet reflector plane's normal be d, and angular velocity be ω (Figure 7.). The polar coordinates of normal vector of sheet reflector plane at time t is

$$(\theta, \phi) = (d, \omega t) \qquad (5)$$

Usually d is very small and we may consider $\cos d$ and $\sin d$ to be 1 and d.

Let the world Cartesian coordinates of normal vector at point (x, y) be $\boldsymbol{x}\ (\boldsymbol{x}, \boldsymbol{y}) = (x(x,y), y(x,y), z(x,y))$. This is unchangeable unless object moves. But as the sensor body rotates, the coordinates of normal vector in sensor-fixed coordinate system ($\boldsymbol{x}'$) becomes the function of time (Figure 8.).

We perform the coordinate translation as

$$\boldsymbol{x}'\ (\boldsymbol{t}) = T^{-1} M T \boldsymbol{x} \qquad (6)$$

where T is the rotation matrix around z axis by ωt, M is the rotation matrix around $Y\prime$ axis by d, and T and M are described as follows.

$$T = \begin{bmatrix} \cos\omega t & -\sin\omega t & 0 \\ \sin\omega t & \cos\omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

$$M = \begin{bmatrix} \cos d & 0 & -\sin d \\ 0 & 1 & 0 \\ \sin d & 0 & \cos d \end{bmatrix} \qquad (8)$$

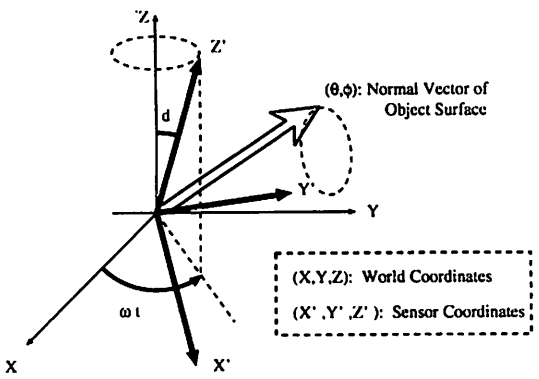


Figure 8. Coordinate Translation.

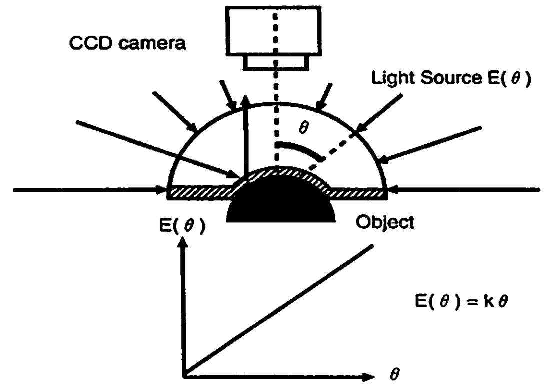


Figure 9. Function of Light Source in Axial Rotation.

Substituting Eq.7,and Eq.8 into Eq.6,

$$x'(t) = \begin{bmatrix} \cos\theta\cos\omega t\sin d + \cos\phi\sin\theta\cos d + \\ \sin\theta\sin\omega t\sin(\phi-\omega t)(\cos d - 1) \\ \cos\theta\sin\omega t\sin d + \sin\phi\sin\theta\cos d + \\ \sin\theta\cos\omega t\sin(\phi-\omega t)(\cos d - 1) \\ \cos\theta\cos d - \sin\theta\cos(\phi-\omega t)\sin d \end{bmatrix} \quad (9)$$

Let the zenithal angle of normal vector at point (x, y) in sensor-fixed coordinate system $\theta(x, y, t)$. As the x' in Eq.9 is already normalized, z coordinate of x' is equal to $\cos\theta(x, y, t)$. We get the following equations.

$$\cos\theta(x,y,t) = \cos\theta\cos d - \sin\theta\cos(\phi-\omega t)\sin d \quad (10)$$

$$= \frac{\cos d}{\cos d'}(cos\theta\cos d' - \sin\theta\sin d') \quad (11)$$

$$(\tan d' = \frac{\sin d\cos(\phi-\omega t)}{\cos d})$$

$$= \frac{\cos d}{\cos d'}\cos(\theta + d') \quad (12)$$

$$\simeq \cos(\theta + d') \quad (\cos d, \cos d' \simeq 1) \quad (13)$$

Therefore,

$$\theta(x,y,t) \simeq \theta + d' \quad (14)$$

$$= \theta(x,y) + \tan^{-1}\frac{d\cos(\phi(x,y)-\omega t)}{\cos d} \quad (15)$$

$$\simeq \theta(x,y) + d\cos(\phi(x,y)-\omega t) \quad (16)$$

Let the spatial function of patterned transparency linear function of zenithal angle θ(Figure 9.). Then, the brightness which we observe is proportional to the zenithal angle of the normal of that point($\theta(x, y, t)$). Therefore, What we must do is to extract θ and ϕ from $\theta(x, y, t)$. We extract θ by taking the time average of Eq.16. We extract ϕ by taking the temporal correlation with $\sin\omega t$ and $\cos\omega t$ as follows.

$$S = \int_0^{2\pi/\omega} E(x,y,t)\sin\omega t dt \quad (17)$$

$$= \int_0^{2\pi/\omega} (\theta + d\cos(\phi-\omega t))\sin\omega t dt \quad (18)$$

$$= \frac{\pi}{\omega} d\sin\phi \quad (19)$$

$$C = \int_0^{2\pi/\omega} E(x,y,t)\cos\omega t dt \quad (20)$$

$$= \int_0^{2\pi/\omega} (\theta + d\cos(\phi-\omega t))\sin\omega t dt \quad (21)$$

$$= \frac{\pi}{\omega} d\cos\phi \quad (22)$$

From S, C, we get ϕ uniquely. Namely, the axial rotation converts the azimuth information ($\phi(x, y)$) to time information (phase).

We must emphasize that all calculations need only the information taken from one pixel, that is, calculations among neighboring pixels are not necessary.

4.2 Experiment and Evaluation

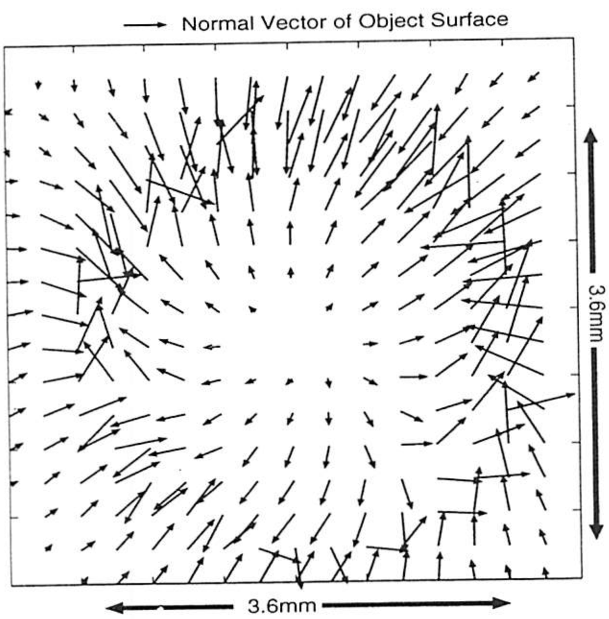
We measured the sphere, 10mm in diameter. The zenithal angle d is 2.5 degrees. We rotate axis by 45 degrees a step and took the image. We repeated it 8 times. By taking average and temporal correlation, we got zenithal and azimuthal angle of each point.

Figure 10(a) shows the surface normal, projected on $x - y$ plane. Figure 10(b) is the reconstructed shape of sphere, by integrating normal vector. From them, we can state as follows:

- Surface normals of the points where object and sensor keep contacting all the time are determined accurately.
- At edge, the obtained normals are extremely distracted. This is because object and sensor don't keep touching. It also means that by detecting discontinuity of obtained normals, we can obtain edges easily.

There have been a few attempts to detect edge, by using spatial filtering matrix[6]. Such method is well known in vision systems. But we must emphasize the fact that deviation of sensitivity among tactile sensing elements is ordinary large, and operation among neighboring pixels is not a good choice. On the contrary, As we stated in Section.4.1, we use only the information taken from one pixel, and calculation among neighboring pixels is not necessary.

(a)



(b)

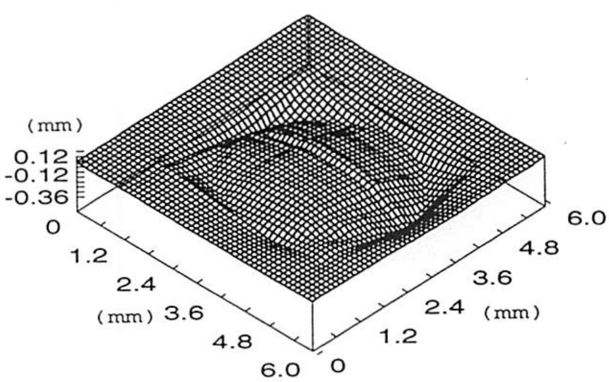


Figure 10. (a)Determined Surface Normal of the Sphere. (b)Reconstruction of Shape by Integration of (a).

5 CONCLUSION

We proposed active tactile sensor. The features of the sensor system are: 1) the body is made of transparent elastomer, 2) deformable reflector sheet is attached on contacting surface, 3) the sensor detect reflected light, and 4) multi dimensional small movement is available.

We classified the movement of sensor by degrees of freedom, considered the available informations about the contacting surface, and evaluated them by experiment as follows.

- Vertical Movement: Shape reconstruction.
- Axial Rotation: Surface normal determination and edge detection.

We emphasized the importance of active sensing scheme in the field of tactile sensing. We confirmed that by simple movement and simple temporal correlation calculus, we can obtain shapes, surface normals, and edges of the contacting object.

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