Combined Tactile and Proximity Sensor Employing Compound-eye Camera

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Abstract We propose an optical sensing device to obtain both tactile and proximity information with high spatial resolution that is necessary while grasping small and intricately-shaped objects using a robot hand. In our proposed device, tactile information is obtained through a light conductive plate, which allows the capture of a tactile image of high spatial resolution using a camera. Proximity information is detected on the basis of stereo matching of a pair of images obtained by two cameras through the transparent light conductive plate. In order to realize this concept in a small device, a compound-eye camera which is composed of a single image sensor and an array of nine micro lenses is introduced. A prototype device provides three visible light and three infrared images for proximity and tactile information, respectively. The performance of the prototype is evaluated through an experiment and the factors affecting its performance are discussed.

Key words: Tactile sensing, proximity sensing, compound-eye camera

1. Introduction

In implementing grasping control for a robot hand, it is necessary to use different kinds of sensors in order to obtain information about the object to be manipulated. For example, the location, posture, and shape of the object are usually obtained using a vision sensor, whereas a proximity sensor is used while approaching the object. Tactile information is required to determine the condition of contact between the object and the robot hand. For use as a tactile sensor, a resistive sensing device based on strain gauges and conductive polymers is commonly used[1]. For use as a proximity sensor, an optical sensing device with an emitter-detector pair is often used[2]. These typical tactile and proximity sensors are based on point measuring, and the spatial resolution provided by them can be low even if multiple sensors are arranged together, thus it may be difficult to detect minute objects and measure a contact condition for intricately-shaped objects.

Therefore, to realize a high spatial resolution, there have been several studies on tactile sensors consisting of a camera and an elastic body[3][4][5][6][7][8]. When a force is applied on the surface of an elastic body, markers embedded in the elastic body move. By locating the positions of the markers and measuring their displacement using a camera, tactile information, such as force, slip, and shape, can be obtained. Based on a similar method, touch detection sensors have been reported in the field of human-computer interface[9]. These sensors are used for obtaining only tactile information, whereas other sensor devices have to be added to the sensing system if other information such as proximity is required.

In fact, a robotic hand, equipped with tactile and proximity sensors, has been developed[10][11]. Several tactile and proximity sensors are mounted on the fingertips and palm of the robotic hand and are used to provide grasping control for objects. However, the spatial resolution provided by these sensors is low, and therefore it is difficult to manipulate small objects.

We have proposed a combined tactile and proximity sensing device using multiple small cameras for measuring both tactile and proximity information at a high spatial resolution[12][13]. In this study, we summarize the characteristics of the proposed sensor device and discuss factors affecting the performance of the sensors with respect to various factors such as sensitivity, and spatial and temporal resolution.

2. Concept of the proposed device

Fig.1 shows our concept of the combined tactile and proximity sensing device, which consists of an light conductive plate (such as a transparent acrylic board), infrared LEDs, and three cameras. Infrared light from the LEDs is introduced to the transparent acrylic board.
Fig. 1 Concept of the proposed tactile and proximity sensing device. Visible-light stereo image pairs and infrared images are used to obtain proximity and tactile information, respectively.

For incident light with an incidence angle larger than the critical angle (defined by refractive index of the medium), a total internal reflection occurs, and the light is reflected inside the acrylic board.

Two of the three cameras are equipped with an infrared cut filter and receive visible light images. As shown in Fig. 1, these cameras can capture the image of both objects A and B through the transparent acrylic board. These two cameras have slightly different view points; thus, output images from these cameras can be used for calculating the distance of the sensor to the objects using stereo matching, and proximity information is thus obtained.

When an object makes contact with the surface of the acrylic board, infrared light is reflected by the object at the contact point, which causes the infrared light to scatter; this scattering is captured by the camera equipped with a visible light cut filter, and thus can be used to obtain tactile information.

In the case of our proposed design, both tactile and proximity information is obtained as images captured by the camera, and thus, the spatial resolution considerably increases compared with that of conventional sensors. In addition, a new feature that our design provides is that tactile and proximity information can be directly compared using the same image coordinates.

On the other hand, this structure requires at least three cameras for implementation. To ensure that the size of the sensor device is sufficiently small so that it can be mounted on the robotic hand, we employ an extremely thin and compact imaging system, a compound-eye camera, which is described in the next section. Major specifications of tactile and proximity sensing, such as spatial and temporal resolution, depend on that of the camera and characteristics of the LED and light conductive plate as discussed in a later section.

3. Prototype of the device

We developed a prototype based on the concept described in the previous section. Fig. 2 shows the picture of this prototype. As a compact multiple camera system, we used a compound-eye camera called TOMBO (thin observation module by bound optics). TOMBO consists of a lens array, a signal separator, and an image sensor and is constructed as an array of elemental parts called units including a lens and a small segment of the image sensor. The TOMBO used in this study has an array of nine units. The lens pitch is 1.2 mm and a focal length is 1.5 mm (horizontal and vertical view angle of unit is approximately 50°). F number is 6.0. Optical filters are placed in front of the image sensor so that infrared and visible light images can be observed for tactile and proximity sensing, respectively. In this study, visible light cut and infrared cut filters are placed on three units at the top row and three other units at the middle row, respectively (Fig. 3).

The image sensor used is a CMOS image sensor (Mi-
cron MT9P031STM) mounted on a camera module (IDS UI-1481LE). The pixel number of the image sensor is 2560×1920 pixels. In our experiments in this paper, we select 1280×960 pixels as pixel number and 26 fps as frame rate through a binning and sub-sampling function of the image sensor, and the resolution of each unit is approximately 300×300 pixels.

A 2 mm-thick acrylic board is placed in front of the compound-eye camera and 25 mm apart. On one side of the edge face of the acrylic board, four infrared LEDs (Toshiba TLN117F) are arranged. Forward current of the LEDs is set to 40 mA, thus resulting in radiation intensity of 7 mW/sr for each LED.

The size of the developed sensor is 35 mm ×42 mm×32 mm, it weighs 40 g.

4. Responses of the device

In the proposed sensor device, each pixel value in the output image represents the information about contact or proximity to the object, and the output image represents the distribution of those sensor informations. Therefore we refer the image or pixel value obtained from the image to as response of the device. We examined the responses of the developed sensor device.

4.1 Tactile sensing

As mentioned earlier, tactile sensing is based on the infrared image obtained by the sensor. For our experiment, we used a white rubber block as an object. When the object makes contact with the surface of the acrylic plate of the sensor, the intensity of some pixels on the infrared image begin to change (Fig.4). In this case, the pixel brightness value became larger when about 10 g of force was applied. In order to detect a contact, the infrared image is binarized. As shown in the top row in Fig.4, a contact pattern was detected with high spatial resolution of the unit of the compound-eye camera, 83 μm in this case (the sensing area is 25 mm × 25 mm, the pixel number of an unit is 300 pixels × 300 pixels).

This enables the sensor to measure the contact area in an extremely precise manner, thus, enabling contact detection even with small objects. In the proposed sensor, some of the requirements for tactile sensors, such as a spatial resolution and number of sensing sites, have been realized at a higher level than the general requirements.

4.2 Proximity sensing and 3D shape measurement

Proximity sensing is based on a stereo pair of visible light images obtained using our sensor. Stereo disparity is calculated through the stereo matching technique; this stereo disparity can be converted to a physical distance value of the object from the camera on the basis of the geometry of a parallel arrangement of units in the compound-eye camera. This distance is

![Fig. 4](image1)

Results of contact detection. An object (rubber block) comes in contact with the surface of the acrylic plate of the sensor (left to right). In the top row, white pixels show detected contact area via binarization of intensity in the infrared images (middle row). The bottom row shows visible light images.

![Fig. 5](image2)

Experimental results of relationship between stereo disparity and distance. Depth resolution (disparity change per distance change) at a particular distance depends on the resolution of the image sensor, and increases for higher resolution values.

![Fig. 6](image3)

Depth images obtained from stereo pairs of visible light images using our sensor.
used for proximity detection. For precise proximity detection, the resolution of the distance measurement is important. We use block matching for stereo disparity computation, such that, in general, the resolution of the distance measurement depends on the pixel resolution. Fig.5 shows the experimental results evaluating the depth resolution for the resolution of the image sensor mounted in the compound-eye camera. In the experiment, the object was moved every 1 mm, and the mean stereo disparity in the object area was computed. In the area near the acrylic board (distance less than 35 mm), the precision of the distance measurement was within 3 mm even if the resolution of 1280×960 pixels was selected. This accuracy is comparable with that of a conventional optical proximity sensor. If the maximum resolution of the image sensor is selected, then the accuracy is within 1 mm.

Fig.6 shows the disparity images computed for three different postures of the target object. In the disparity images, brighter pixels indicate larger disparity corresponding to a position closed to the sensor. The window size of the stereo block matching was 5×5 pixels. The quality of the depth image may degrade if the target object is large and textureless, therefore a semi-global block matching\(^{17}\) was introduced to improve the quality of the result. These images provide information about the 3D shape of the object and can be used for determining the position and posture of the robotic hand that is suitable for stably grasping the object.

4.3 Response to minute objects

With high spatial resolution of tactile sensing, the proposed sensor can be used for detecting small object as well. We used a 2.0 mm × 1.2 mm chip resistor as an object to be measured. In the binary image showing the detected contact pattern, the area of contact on the image coordinate was 327 pixels, which was close to the expected value from theoretical resolution of the sensor, i.e., 83 μm. In this case, a thin silicon rubber sheet was attached on the contact surface of the acrylic plate so that the sensor responds well for rigid objects.

5. Factors affecting to resolution and sensitivity

The responses of the proposed sensor depends on several factors. These factors are divided into two classes: (a) factors related to the object, and (b) factors related to the sensor device. Regarding (a), the response of the proximity sensing depends on the appearance of the object because this sensing is based on a stereo matching computation. The tactile sensing are based on the measurement of the reflected light from the object, the responses of the sensor are affected by the optical properties of the surface of the object, such as spectral reflectivity. Because those are not practically controllable in real situations, we discuss the factors under (b), i.e., the ones related to major elements in the sensor device here.

5.1 Specifications of image sensor

In general, the spatial and temporal resolution of the proposed sensor depends on the specifications of the
image sensor mounted on the compound-eye camera. Larger the pixel number of the image sensor, higher is the spatial resolution obtained in the case of both tactile and proximity sensing. A higher sensitivity (S/N ratio) of the image sensor leads to higher sensitivity in both tactile and proximity sensing. There is a trade-off between spatial and temporal resolution in standard image sensors in which the output image is read using scanner circuits. In this study, the frame rate of the image sensor is 6 fps and 100 fps at pixel resolutions of 5M and QVGA, respectively.

5.2 Intensity of light source

In tactile sensors, which are based on the other principle such as resistive sensing devices, the sensing sampling rate is in the range of several hundred Hz to 1 kHz. As mentioned in the previous section, the temporal resolution depends on the frame rate of the image sensor. High-speed image sensors are currently available, however, the observed images become darker and the sensitivity decreases for such a high frame rate. For proximity sensing, the sensitivity can be increased by applying higher illumination intensity, as is the case for normal imaging. On the other hand, for tactile sensing, the sensitivity can be improved by increasing the intensity of infrared LEDs attached to the acrylic board.

We examined the response of tactile sensing in the proposed sensor in the case of higher frame rates, and evaluated the effect of increased intensity of LEDs. For that experiment, a high-speed camera (Optronis CR450) was used for tactile sensing at high frame rate. Further, a high-intensity infrared LED (OSRAM LD274) is used and 16 of those are attached around the acrylic board. Fig.8 shows the experimental results. When the frame rate increased, the response which was obtained as the maximum value in the infrared image decreased. When the forward current of each LED increased and the intensity of light provided became higher, the response increased. In addition, by increasing the number of LEDs could increase the response as well. These results suggest that it is possible to increase the temporal resolution of the proposed sensor to more than 1kHz with a certain sensitivity by increasing the intensity of incident light provided to the light conductive plate.

5.3 Characteristics of light conductive plate

As previously specified, increased intensity of the light source causes the sensitivity of tactile sensing of the proposed sensor to increase. Other factors affecting the sensitivity of tactile sensing are the optical characteristics of the light conductive plate. A total internal reflection will occur in the acrylic board occurs when the angle of incidence of the incident light is larger than the critical angle \( \theta_c \) which is given by Snell's law.

\[
\theta_c = \sin^{-1} \frac{n_2}{n_1}
\]

where \( n_1 \) and \( n_2 \) are the refractive indexes of the medium at the incidence side (light conductive plate in this case) and other side, respectively. The material of the light conductive plate is acrylic plastic and the experiments in this study were performed in air, \( n_1 = 1.5 \) and \( n_2 = 1.0 \). In this case, \( \theta_c = 41.8^\circ \). If the sensor is used underwater, the medium that is in contact with the surface of the light conductive plate is water, which has a refractive index \( n_2 = 1.33 \), and in that case, \( \theta_c \) increases to more than 60°. If the critical angle is larger, less light is expected to reflect from the boundary because a light ray having an incident angle smaller than the critical angle passes through the boundary to the outside of the plate. In fact, the tactile response obtained underwater is smaller than that in air in the
Fig. 11 Experiment for autonomous object (white rubber block) following based on the proximity information. Visible light image (top left), disparity image (bottom left), and picture of the robot (right) in each image. The robotic hand is controlled so that it maintains a constant distance from the object.

Based on this principle, the sensitivity of tactile sensing can be increased by using a material with higher refractive index as the light conductive plate. If the refractive index of the plate is 1.6, the critical angles in air and underwater are 38.7° and 56.3°, respectively, which are smaller than the previous case; thus, sensitivity can be improved.

6. Application to robotic hand control

We apply the proposed sensor to aid in controlling the robotic hand.

For the experiment, the sensor device is mounted on a 6 degrees of freedom robot manipulator (Denso academic robot VE026A) as a gripper which holds objects between the acrylic plate of the sensor and another plate (Fig.10). Output images from the compound-eye camera are obtained through USB2.0 interface and processed by a PC. Then, an appropriate motion of the robot is computed and this is sent to the robot as a control command. In this system, the robot motion can be automatically controlled based on the tactile and proximity information obtained through image processing.

The image processing was done at 26 fps which is the same rate of the camera output.

Fig.11 depicts an autonomous object following motion based on the proximity information. When the object (cross-section area is 15 mm × 25 mm) moves left and right, the robotic hand follows the object maintaining a constant distance, 15 mm. This function can be used for positioning the robotic hand before grasping the object so that the hand can stably grasp the object.

Fig.12 shows an autonomous picking up action based on the tactile information. After starting to close the hand grip, the robotic hand stops further tightening the grip and picks up the cylindrical object with 8mm diameter if the detected contact area reaches a certain value. Here, the proposed sensor provides both contact and depth images using the image coordinates with the same scale, and the condition to trigger a pick-up could be defined as a ratio of contact area and overall size of the object as well as a constant value.

7. Conclusion

We proposed an optical sensing device to obtain both
tactile and proximity information with high spatial resolution. By using a compound-eye camera, we constructed a compact device so that the sensor can be mounted on the robotic hand. Through experiments using the robotic hand, we verified that the proposed device can obtain several kinds of information which is needed before and during grasping operation, such as size, shape, proximity, and contact of the object with high spatial resolution. In addition, we discussed the factors affecting the performance of the sensor to show a guideline for determining the specifications of the elements in the sensor and in its further development.

References