A new sensor system for simultaneously detecting the position and incident angle of a light spot

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A New Sensor System for Simultaneously Detecting the Position and Incident Angle of a Light Spot

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Abstract: The present paper describes a newly devised sensor which has the ability to detect the two-dimensional position and the one-dimensional angle of a light spot simultaneously. Ordinary laser-based measurement systems utilize CCD or PSD sensors. These conventional sensors can detect only a light spot's position. When the sensor can detect the incident angle of a light spot as well as the position, the sensor has a wide range of applicability. The sensor consists of two linear array-type sensors whose depth positions are slightly different. We have designed and built a prototype sensor system. We experimentally verified the practicable accuracy of the present sensor system. We also applied the present sensor system to two typical laser-based measurement systems: 2-D position measurement, and 3-D shape measurement for specular objects. Experimental results show that the sensor system was applicable to a laser-based measurement system.

Keywords: Position measurement, angle measurement, CCD, PSD

1. Introduction

Most laser-based measurement systems such as rangefinders and the motion capture system, for the sake of acquiring the spatial information, are often utilized so as to receive the reflected light after light has been projected onto an object, or to directly receive the light from a light source attached to the object. The laser is often used for such a system because it has the advantage of high intensity, high directivity, and monochromaticity[1]. In measuring systems, the high directivity of the laser is useful from two viewpoints: the transmission of the energy of the light and the maintenance of the optical path. The transmission of the energy of the light is often used for measurement. By comparison, maintenance of the optical path has seen less use. Since information of the optical path includes information on the position or orientation of objects, the utilization of the information on the optical path in measurement has great potential for development in laser-based measurement systems.

In order to acquire information on the optical path, it is necessary to have a sensor that is able to detect both the position and the incident angle of the light. To our knowledge, such a sensor does not yet exist. A sensor exclusively for detecting the position of a light spot and a sensor exclusively for detecting the incident angle have been already developed. The sensor typically used for the former is a CCD[2] (charge coupled device) or a PSD[3] (position sensitive device). An example of the latter has been marketed by the Hamamatsu Photonics Co[4]. However, a sensor that has the ability to simultaneous detect the position and the angle of a light spot has not yet been developed. Actually, for the above described application, conventional sensors such as the CCD or PSD have been used. Ordinary laser-based position measurement techniques using a CCD[5][6] or PSD[7][8] have, as a result, employed the algorithms using exclusively the light spot's pixel position.

If an image sensor can detect the incident angle of a light spot as well as its position, it can be expected that an image sensor can be effectively applied to a number of situations. For example, ordinary laser rangefinding systems have been based on the premise that the image sensor used the system can acquire only the position of the light, and their systems hence have some parameters that have to be determined in advance of the measurement and geometrical limitations that are difficult to avoid[9],[10]. The development of the new-type rangefinder which has the ability to detect both position and the incident angle can reduce such parameters and limitations.

On the other hand, a sensor system that can detect both position and the incident angle can also measure the surface orientation of specular objects. The measurement of the surface orientation of specular objects is a difficult problem[11], because the orientation of specular objects can not be not determined based on only the light spot's position. However, the acquisition of the data regarding the incident angle easily allows the detection of the surface orientation of specular objects. In this way, a laser-based measurement system using both the position and the incident angle of a light spot makes it possible to develop a measurement system beyond the framework of conventional measurement systems.

The present paper describes a novel sensor system that has the ability to detect a light spot's incident

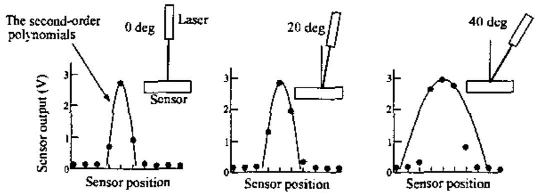

Fig.1 Intensity distribution of a light spot which is projected to the image sensor plane

position and angle simultaneously. In this study , we focus on the one-dimensional sensor type, and studying the feasibility of such sensor system. This system consists two array-type sensors whose depth positions are slightly different. The proposed sensor system detects the pixel position of the light spot using the peak position of the deeper-sided sensor array. In addition, the sensor system also detects the incident angle of the light spot in terms of the difference between the two peak positions of the light spot that their two sensor arrays produce.

We have designed and built a prototype two-dimensional sensor system in which the proposed principle is implemented. We first examined its accuracy by measuring the position and the incident angle of the prototype sensor system.

2. Principle of mechanism to detect the light spot's angle and position

As a first step for determining the basic concept of the sensor system under consideration, we studied the intensity distribution of a light spot which is obliquely projected to the image sensor plane.

Fig.1 shows this distribution. The x-direction shows the direction of the image plane of the sensor, and the y-direction shows the output of the sensor. In these figures, the horizontal axis illustrates the pixel position of the sensor, the vertical axis shows the intensity of each pixel of the sensor, and the solid lines show the approximated curves determined by the second-order polynomial using the three intensity values, that is, the peak value and the values of the adjacent pixels. We projected the light spot at 0, 20, and 40 degrees with respect to the sensor. These figures reveal the following two characteristics of oblique projection:

(1) In optical theory, the larger the incident angle is, the greater the extent of the asymmetry of the intensity distribution. However, in the case of a laser, the asymmetry of the intensity distribution is less marked than the obliquity of the beam onto the sensor. We here estimated the degree of the asymmetry from the difference between the actual peak positions of the intensity distribution and the positions of the distribution's barycenter in the x-direction. If the distribution is symmetrical, then the two positions should be of the same value. According to this estimation, the distance at 0-degrees, 20-degrees, and 40-degrees are 0.02mm, 0.12mm, and 0.14mm, respectively. The half-width of each intensity distribution was about 1.5mm. The plot of both 20-degrees and 40-degrees indeed display a greater degree of asymmetry than does that of 0-degrees, though the difference between the asymmetry at 20-degrees and that at 40-degrees is small.

(2) It is known that the intensity distribution of the laser is well described by a Gaussian distribution under vertical projection onto the image plane of the sensor. However, when the laser is obliquely projected onto the sensor's image plane, application of Gaussian distribution may cause a large error in the calculation of the peak positions of the intensity distribution due to the asymmetry of the distribution. From Fig.1, we found that even if the intensity distributions were asymmetrical as a whole, their distributions near the peak were locally symmetric with respect to each peak position, and could be approximated using the second order polynomial.

Based on the above characteristic (2), the peak positions should be accurately detected for oblique projection onto the sensor. However, the observed characteristic (1) revealed that it is in actuality difficult to acquire information regarding the incident angle exclusively by using the asymmetry of one intensity distribution alone.

We therefore arrived at the idea of detecting the position and the incident angle by using the outputs of sensors located at different positions in the deep direction instead of using the intensity distribution of one sensor. Based on this principle, we used a slit ray instead of a light spot as a light projected onto the proposed sensor system. In this case, if we use a spot light instead of a slit ray for our sensor, we need to shift the spot light in the direction perpendicular to the image plane because of the shape of the small circle in the spot light. The spot light has a serious disadvantage in terms of time consumption and deterioration of accuracy in the measuring process. Moreover, the slit ray is projected at a direction perpendicular to both the horizontal plane and the image plane of the sensor.

Fig. 2 shows the basic construction of the proposed sensor system and the intensity distributions of the slit ray onto the sensor when the slit ray is projected at an angle with respect to the sensor plane. The sensor system consists of two linear-type sensors(a front sensor and a rear sensor), which are arranged at a short distance from each other in the z-direction, and are arranged in the x-direction. The slit ray is projected at a given angle to the x-direction from the z-direction. The vertical axis of the figure is the intensity received by each sensor. Black circles show the measured values,

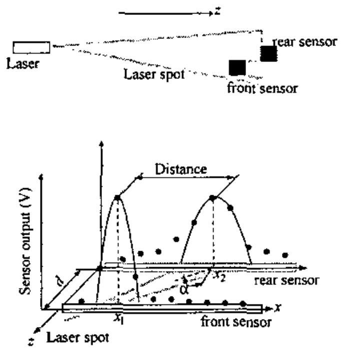

Fig.2 Basic construction of the proposed sensor system and the intensity distributions of the slit ray onto the sensor

and the broken lines are approximated by a curve of the second-order polynomial, which uses the peak value and the two values of the adjacent pixel of the sensor.

When the slit ray is projected at an angle to the image plane of the sensor, the distribution of the received light intensity on the sensor demonstrate the two following tendencies:

(1) The distribution of the intensity near the peak in both the front sensor and rear sensor can be approximated using the second order polynomial even if the angle of the light to the sensor varies.

(2) When the incident angle of the light varies, the distance between the peak position detected by the front sensor and the rear sensor varies as well. The larger the incident angle is, the larger the distance is.

According to the results of the above preliminary experiments, we therefore estimated the positions and the incident angles of the slit rays that were obliquely projected to the proposed sensor as follows: we regarded the peak position of the intensity distribution in the rear sensor as the actual position of a slit ray, x, that is to say, as it is expressed by equation(1);

$$x = x_2 \tag{1}$$

When the distance between the front sensor and the rear sensor is d, and x_1 and x_2 is the actual peak position of the front sensor and the rear sensor, respectively, then the incident angle α is calculated using equation(2).

$$\alpha = \tan^{-1}\frac{x_2 - x_1}{d} \tag{2}$$

3. Sensor configuration

Fig.3 shows the basic configuration of the proposed sensor. The operating principle of the image sensor used for this rangefinder is almost the same as that of our previous workes (reference 3 and 4). What sets the present image sensor apart is the use of a half-mirror and area image sensor system. The light reflected from the object is divided into two directions by the half-mirror and directed toward two area image sensors.

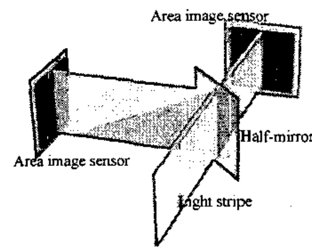

Fig.3 Optical path of the proposed image sensor

Fig.4 shows the principle by which the image sensor detects the incident angle of the light. The figure displays the distribution of area sensor 1 and area sensor 2 around the same axis. If the light hits the line AB of the figure vertically, then the peak positions of area sensor 1 and area sensor 2 are equal. However, when the light hits the line AB obliquely, the peak positions of area sensor 1 and the area sensor 2 differ and the deviation is proportional to the magnitude of the incident angle hitting the line AB of the figure. The position and the incident angle of the light is then calculated as follows:

$$x = x_2 \tag{3}$$

$$\varphi = \tan^{-1}\frac{x_2 - x_1}{l_2 - l_1} \tag{4}$$

4. Prototype sensor system

Fig.3 shows a photograph of the prototype sensor system. The test configuration consisted of a light-stripe generator, and the prototype sensor system.

The light stripe generator used a semiconductor laser diode that had a 670nm wavelength and a 10mW output. It was positioned on a precision rotation stage, which was mounted onto a precision translation stage. The lens was cylindrical, with a height of 50mm, width of 50mm, and focal length of 40mm.

The sensor system consists of a half-mirror and area image sensors, which composed of mutiple linear CCD image sensors. The half-mirror is a cubic construction, with dimensions of 50mm × 50 mm × 50mm.

The image plane of the image sensor consists of two

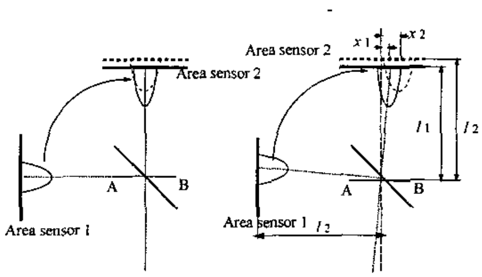

Fig.4 Photograph of the prototype sensor.

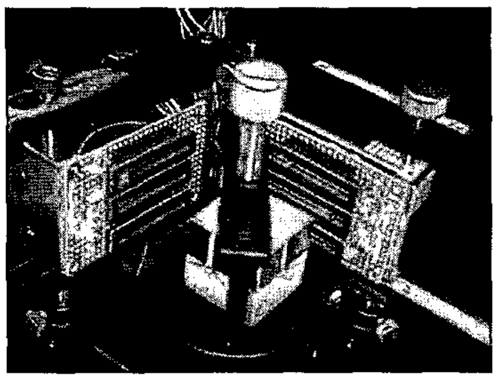
Fig.5 Photograph of the prototype sensor

planes oriented orthogonally to each other. The distances between the planes and the center of the half-mirror are 40mm and 45mm, respectively. Each image plane is equipped with three linear CCD image sensors containing 2048 pixels that are 14 μm in size. Thus, this image sensor can acquire three sets of data simultaneously. The received positions are interpolated by the least square method.

5. Characteristics of the image sensor

Fig.6 shows the output of positions by our prototype image sensor versus the actual positions when the light was projected to the sensor at 0, 5, and -5 degrees. The data are shown as the upper, middle, and lower lines of this figure. The solid line was drawn by the least square method. The maximum relative error of the measured data was 0.89% in these figures. All the measured results achieved almost the same level of accuracy, ranging from 0.7% to 1.1%.

Fig.7 illustrates the results of the sensor's angle measurements. In this experiment, we changed the sensor from -10 to +10 degrees. The horizontal axis shows the variation of the given angles, or φ_1, while the vertical axis shows the sensor output, or φ_2. The solid line in the figure represents $\varphi_1 = \varphi_2$. In this figure, the maxi-

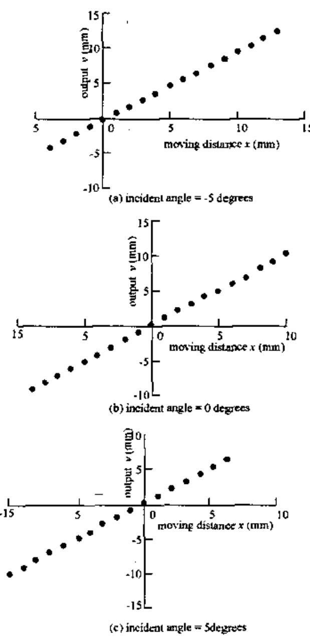

Fig.6 Output of the positions by the prototype sensors system versus actual positions

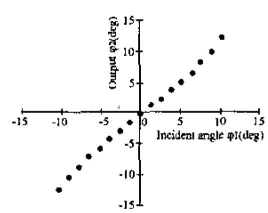

Fig.7 Output of the angles by the prototype sensors system versus actual angless

mum relative error is 1.12% and the maximum absolute error is 1.13 degrees.

From these results, it is clear that the proposed sensor has the degree of accuracy needed for many laser-based application.

6. Conclusions

We proposed a new sensor system for simultaneously detecting the two-dimensional position and the incident angle of a light spot. The sensor consists of a half-mirror and six linear sensors, oriented orthogonally to each other, and detects the incident angle of the light based on the difference of peak positions between the two sensor elements. Unlike the previous image sensor, the proposed image sensor has the ability of detecting three two-dimensinal positions and three incident angles. We have designed and built a prototype sensor system whose maximum errors of position measurement are in the range of 1.81% - 1.85%. The maximum error of angle measurement is 0.46 degrees without the lens, and is 1.6 degrees with the lens. Experimental results demonstrate that the sensor system could be practically applied to a laser-based measurement system.

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