DEVELOPMENT OF AN OVERALL DIRECTION-OF-ACTION SENSOR FOR ROBOTS

Tokuji Okada

Electrotechnical Laboratory
1-1-4, Umezono, Sakura-mura,
Niihari-gun, Ibaraki, 305 Japan

ABSTRACT

Development of an optical sensor for measuring overall direction-of-action is treated. The measurement principle is based on distortions found in the projected image of a ball moving freely in a spherical vessel under the influence of the acceleration of gravity and motion. The measurement is carried out in a static condition. Thus, the sensor output stands for the direction of the gravitational field. Experimental results are presented to show that the angular errors are within 12 degrees for the overall direction. This sensor can be widely applied for measuring angular variations from the direction of the gravitational field.

I INTRODUCTION

Angular values of joints are available to detect the orientation or direction of an end effector of robots. In a multijointed system, it requires a lot of computation to determine the orientation or direction, and the load becomes larger when the system has many joints like the nose of an elephant. Therefore, sensors for the direction measurement are required, however, direction sensors of which the mechanisms are unified like a gyroscope have still not been developed [1,2]. Two parameters expressing the direction are now measured separately by means of cantilevers and pendulums. These are suitable to detect the direction in a specific plane, but a few drawbacks can be pointed out in measuring an arbitrary direction. In order to solve these problems, we proposed two methods for direction measurement [3].

In this paper, we describe the development of a direction sensor based on the second method in [3]. This sensor uses the projected image of an opaque ball housed in a bigger transparent spherical vessel and can measure the overall direction-of-action. First, an outline of the measurement principle is given. Secondly, we describe the design of the sensor head and procedures to extract directional information from the projected image. Thirdly, experimental results which show the usefulness of the sensor for measuring all the directions are presented.

II PRINCIPLE OF DIRECTION MEASUREMENT

Sensor equipment is basically shown as in Fig.1(b). It is composed of a point source of light, an area sensor, a transparent medium having a spherical vessel, an opaque ball housed in a spherical vessel, and transparent liquid covering space of the vessel. The opaque ball can move freely, since the ball is housed in the vessel with sufficient liquid room. Therefore, by locating a weight in the center of the opaque ball, the ball moves under the influence of the acceleration of gravity and motion so as to indicate their combined direction. Then, the ball reaches its equilibrium state. The position of the ball in the vessel is determined by using an image

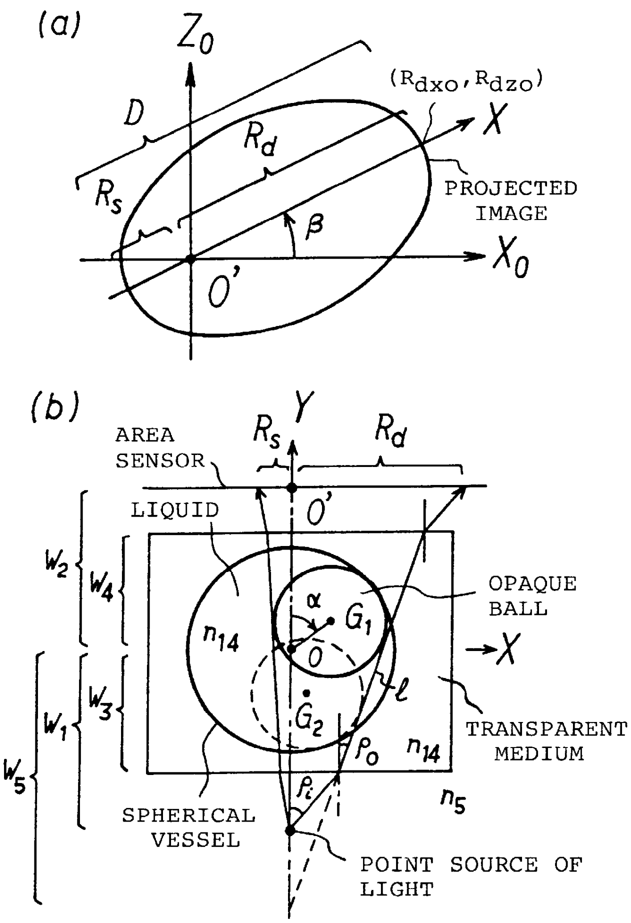

Fig.1. Relationships between direction of the ball and its projected image.

in the photosensitive area of the area sensor, since the image is obtained by applying lights from a point source of light to the vessel. Therefore, the direction in which the ball exists, i.e., the combined direction of the acceleration, is measured. This is an outline of the measurement principle. Next, we explain the details of this principle.

For reducing the complexity of the projected image, the conditions should be such that both the planes of incidence and refraction of a transparent medium are parallel and also refractive indices of both the transparent medium and the transparent liquid are the same. By adopting these conditions, the image is simplified to become nearly equal to an ellipse which distinguishes between interior darkness and exterior brightness in the photosensitive area. Based on these conditions, the image contour as shown in Fig.1(a) is formed by a set of lights touching the opaque ball, and the light arriving at the farthest point from origin O' of the photosensitive area takes the route as shown in Fig.1(b). In Fig.1, the direction of the ball is expressed by parameters α and β. In order to determine these two parameters, we use R_d and R_s data which are defined as the farthest distance and the nearest distance from origin O' to the elliptic contour in the photosensitive area. Rectangular coordinates (R_{dxo},R_{dzo}) of the point related to R_d data are also used. It proves that the contour positions related to R_d and R_s data are located opposite directions from origin O'. Symbolic notation D denotes the summation of R_d and R_s.

Notice that the angle of incidence, ρ_i, between the incident light and the normal is calculated from the following equation (see[3]),

$$E_1\tan^4\rho_i+E_2\tan^3\rho_i+E_3\tan^2\rho_i+E_4\tan\rho_i+E_5=0, \quad (1)$$

where $E_1,E_2,\cdots,E_5$ are constants related to R_d data. But in our sensor design, the valid condition is

$$\left(\frac{n_{14}}{n_5}\right)^2(1+\cot^2\rho_i)-1=\left(\frac{n_{14}}{n_5}\right)^2\cot^2\rho_i, \quad (2)$$

where n_{14}, n_5 are the refractive indices of the transparent medium and surrounding medium, respectively. This approximation yields a tangential component of ρ_0 expressed simply as

$$\tan\rho_0=\left(\frac{n_5}{n_{14}}\right)\tan\rho_i, \quad (3)$$

where ρ_0 is the angle of refraction. The unknown parameter ρ_i is thus uniquely obtained by solving the equation

$$\rho_i=\tan^{-1}\frac{R_d}{(W_1-W_3+W_2-W_4)+(n_5/n_{14})(W_3+W_4)}. \quad (4)$$

The value of ρ_i is used to compute the center position of the opaque ball in the coordinate system (X,Y). In fact, its axial component along the X-axis is obtained by solving a quadratic equation (see eq. (25) in [3]), and then, the axial component along the Y-axis is obtained. But in general, two solutions, i.e., $G_1(x_1,y_1)$ and $G_2(x_2,y_2)$, are obtained ($y_1 \geq y_2$), since the ball touches light path ℓ in Fig.1(b) in the upperside and downside of the vessel. When the ball is near to the light source, its projected image becomes large, but when the ball is far from the light source, the image becomes small. When light path ℓ is in contact with the sectional circle of the vessel, the center position of the ball is determined uniquely since two points, upperside and downside, join together. This critical position is physically determined. We use symbol D_c for the value of D in the critical position. The value of D_c is calculated from

$$D_c=\left\{\frac{n_{14}}{n_5}(W_1-W_3+W_2-W_4)+W_3+W_4\right\}2W_5^2R_3 \Big/\left\{W_5^2-(R_2-R_3)^2\right\}\Big/\sqrt{W_5^2-R_2^2}, \quad (5)$$

where R_2 and R_3 are radii of the vessel and the opaque ball, respectively. And W_5 is the distance between center O and the position of an observed light source such that

$$W_5=W_3+(n_{14}/n_5)(W_1-W_3). \quad (6)$$

By using the physically determined value D_c, the true position of the ball is chosen from the candidates (x_1,y_1) and (x_2,y_2). That is, candidate (x_1,y_1) is correct when the D data is less than D_c, but candidate (x_2,y_2) is correct when the data is greater or equal to D_c. Thus, true position of the ball can be decided. Denote the position with (x,y), then two parameters expressing the direction of the opaque ball are given by

$$\alpha=\cos^{-1}(y/(R_2-R_3)); \quad (7)$$

$$\beta=\tan^{-1}(R_{dzo}/R_{dxo}). \quad (8)$$

III DESIGN OF SENSOR HEAD

Sensor head design is sketched as shown in Fig.2. The magnitude of the image becomes large because of the light radiating from a point. But in reality, the sensor is limited to a small extent in its photosensitive area. Therefore, the screen and ball-shaped optical lens are used for image reduction. The screen is translucent and attached to the refracting surface of the transparent medium. The lens casts the image on the screen to the area sensor without protruding from its photosensitive area. A point source of light is realized by placing a pinhole closely to the lamp. A pinhole is bored into the metalic board having a thickness of 0.05mm, with a radius of 0.35mm. Cylindrical bakelite connects the board with the transparent medium. These components are joined with adhesive material. The transparent medium is made of BK7 glass with a refractive index of $n_d=1.51635$. The spherical vessel is

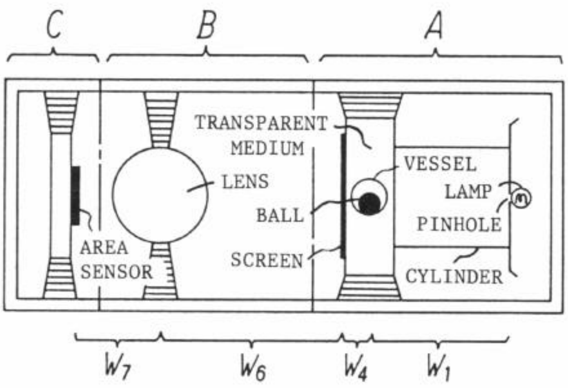

Fig.2. Design sketch of the sensor head.

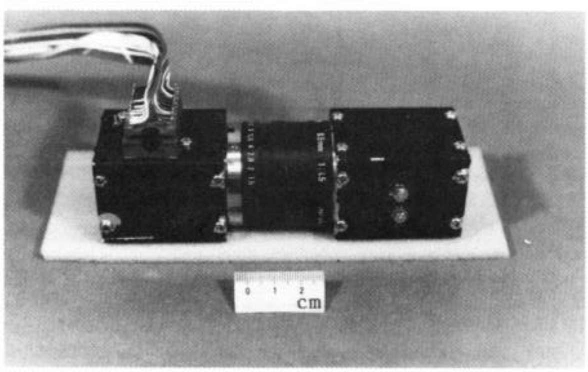

Fig.3. View of the sensor head.

produced by pasting two 6mm thick plates of glass having hemispheres in their centers. In the pasting process, a ball of steel with a radius of 2.375mm which is in wide use as a ball bearing is captured; and thus, the media having a spherical vessel with a radius of 4mm in which the opaque ball is housed is made.

Notice that the liquid in the vessel is considered to be equal to its surrounding medium in the refractive index, in addition to its transparency. Such liquids as cedar oil and anisole are considered for this use, since their refractive indices are nearly equal to that of BK7 glass. But these are extremely different in viscosity. That is, the former is sticky and the latter is lacking in stickness. It has been proven that these liquids fail to react chemically and are miscible with each other. Therefore, the liquid containing one part of cedar oil and two parts of anisole is obtained and used to fill the space of the vessel. One plate of glass has a rectangular groove of $0.8 \times 0.8\ mm^2$ for the injection. By using an injector, the space of the vessel is filled with the blended liquid. Outer end of the groove is adhered with a silicon film so as to seal the liquid from evapolation. The blended liquid is shown to be satisfactory for the aforementioned conditions and suitable for damping the mobility of the ball.

When light from the pinhole enters into the transparent medium of the glass, the light runs straight in the media including the vessel since the refractive indices of the glass, liquid and adhesive connecting two plates of glass are in the neighborhood of 1.51. Optically diffusible 0.02mm thick polyethylene film is attached to one side of the medium from which the light comes out. This film acts as a screen. Also, the film makes it possible to visualize the image on the screen from behind, since the film is translucent. Thus, a silhouette of an opaque ball is brought about on the screen and the image on the screen is optically available for succeeding process. The above-mentioned parts are in rectangular box A in Fig.2.

In box B adjacent to box A, an optical lens is installed to cast the image on the screen to an area sensor in a reduced form. The lens is BaK4 glass, with a refractive index of n_d=1.58663, having a ball shape with a radius of 7.9mm. The distances from the center of the lens to the screen and to the photosensitive area are W_6=39.05mm and W_7=13.69mm. In box C, an area sensor is installed having a photosensitive area of $4.1 \times 4.1 mm^2$. These boxes are screwed on to be arranged on a line connecting the centers of the pinhole, spherical vessel, ball lens, and area sensor. A view of the sensor head is shown in Fig.3. The dimensions of the head is 38mm x 38mm x 140mm .

IV CALCULATION PROCESS

By using a ball lens, a reduced copy of the image on the screen is cast onto the area sensor. But in reality, nonlinearlity in the image reduction is recognized since the reduction rate depends on the height of the image from the optical axis (radiate length). That is, the rate becomes large as the image on the screen separates from the axis. This is caused by the spherical aberration of the lens, and this fact implies that the true position of the image on the screen is not obtained by simple magnification. Thus, the height-dependent reduction rate is obtained. Consider parameter h and magnifying factor C_r for the height of the image on the photosensitive area and the reciprocal of the reduction rate, respectively. These relationships can be expressed in the form $C_r=C_2 / (h+C_1)$, where C_1 and C_2 are constants. The values of C_1 and C_2 are determined by applying the least square method to the data obtained in the experiment prior to the practical direction measurement. Noted that the area sensor has a pyrex window with a thickness of 0.7mm and a refractive index of $n_d = 1.474$. This window serves for scaling down the image on the photosensitive area, however, its reduction rate is considered in determining relationships between h and C_r. Thus, factor C_r means the reciprocal of the total reductions related to the lens and window. In a practical measurement, the data of R_d, (R_{dxo},R_{dzo}), and R_s used in section II are given by products of the C_r value and original data of r_d, (r_{dxo},r_{dzo}), and r_s which are detected from the sensor in much the same way as the data of R_d, (R_{dxo},R_{dzo}), and R_s are obtained. The flowchart to calculate the two parameters, α and β, is shown in Fig.4 .

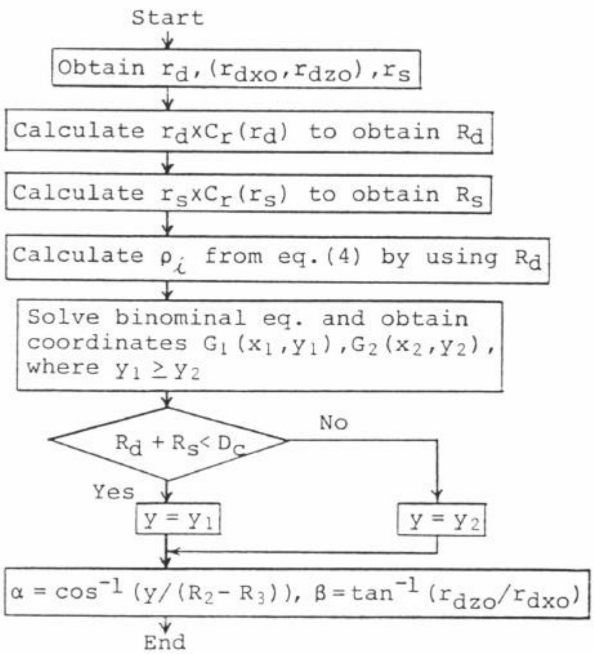

Fig.4. Flowchart for calculating two parameters α and β.

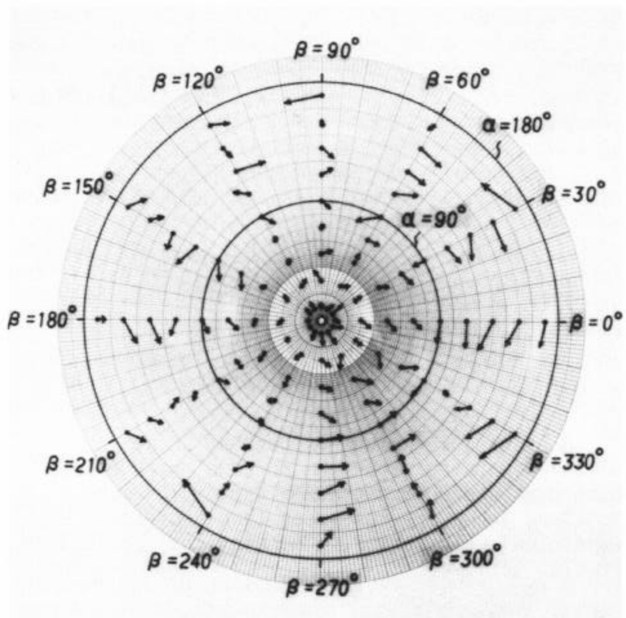

Fig.5. Experimental results of the direction measurement.

V RABORATORY RESULTS

In the experiment, the two parameters, W_2 and W_4, in Fig.1(b) are equal and the other parameters have such values that W_1=17.0, W_2=W_3=W_4=6.0, W_5=22.676, W_6=39.05, W_7=13.69, R_2=4.0, R_3=2.375 in millimeters, and that n_{14}=1.516, n_5=1.0. The experimental results of the direction-of-action measurement in a static condition are shown in Fig.5. In the figure, angles α and β are plotted on the radial and circumferential scales, respectively. The origins of the arrows denote the calculated data, but the heads of these arrows point out the experimental results. Thus, the segments of these lines with arrows mean the angular errors. In the experiment, the approximate equation (2) is utilized since the left and right terms are 18.75 and 17.44 in the maximum amount. The result obtained under this condition shows that the errors of angles α and β are within 12 degrees in all directions. The time required to measure the direction is within 500 milliseconds.

VI CONCLUSIONS AND FUTURE APPLICATIONS

An overall direction-of-action sensor has been developed. In the experiment, the direction is measured under static conditions, that is, the sensor is used as a gravity sensor. Experimental results have confirmed that measurement error is within 12 degrees in all directions and the time required is within 500 milliseconds.

The ball-shaped lens is used in the design of the sensor head since the area sensor is limited to a small extent in its photosensitive area. If the area is wide, the lens is not needed anymore. Then, the sensor could be revised with better accuracy, signal processing which is more simplified, a reduction in size, thus making it more useful.

The direction of the gravitational field is utilized to detect the direction of the end effector of a robot. Therefore, the sensor is useful in controlling the direction of the robot. In particular, it is effective in such a robot having more degrees-of-freedom in motion. Also, the sensor would be applied to systems like platforms, inverted pendulums, and legs, since the direction of the gravitational field is inevitable for preventing them from inclining, shaking, and falling down.

ACKNOWLEDGEMENT.

I would like to thank the members of the robotics group at the Electrotechnical Laboratory for their helpful discussions.

REFERENCES

[1] Nitzan, D. "Robotic Sensors in Programmable Automation," Technical Note 183, SRI International, Menlo Park, California, March 1979.

[2] Harmon, L. D. "A Sense of Touch Begins to Gather Momentum." Sensor Review 1:2 (1981) 82-88.

[3] Okada, T. "New Methods for Direction Sensors by Using Projected Image" In Proc. ISIR-81. Tokyo, Japan, October, 1981, pp.179-186.