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RECOGNITION OF SHAPE BY MEANS OF ACTIVE ANTENNA USING QUARTZ RESONATORS

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Abstract − This paper deals with the application of a quartz resonator to a force sensor installed into an active antenna for use in recognizing an environment. When the antenna makes contact with the environment, the force sensor can detect the contact force and the contact position. Shapes of a rectangular plate, a circular plate and a rectangular parallelepiped were recognized by the active antenna.

Keywords Quartz resonator, Active antenna, Shape recognition

1. INTRODUCTION

Recognition of the environment using tactile sensing can play an equally important role to visual sensing in the field of robotics. An active antenna, based on the concept of an insect antenna, has been suggested as a suitable tactile sensor for use in recognizing the environment in recent years. A few sensing systems have been proposed for such an active antenna [1) 2) 3)]. However, they have not been able to easily acquire information about the nature of the contact or with the required high reliability in real-time. This has all served to prohibit improvements in active antenna technology.

A robot sensor, such as an active antenna, usually coexists with an actuator, which generates electrical noise. Accordingly, it is a requirement that the sensor is insensitive to the noise. Many of the force sensors used in robotics utilize strain gauges, conductive rubbers, piezoresistive elements and so on. Since the output of these devices is usually a low-level analogue signal, the sensor performance is readily affected by electrical noise. Therefore, these sensors often require a noise-reduction filter, despite the fact that the filter restricts the bandwidth, and they also often require an amplifier and an A-D converter to counteract the analogue output and low level.

On the other hand, a force sensor using a quartz resonator is inherently insensitive to noise because the output is a frequency shift caused by an external force. The output can easily be converted into a digital signal through a frequency counter. The digital signal can be directly connected to a computer without an A-D converter. The force sensor also has a fast response, a high sensitivity and a high resolution. Furthermore, since the frequency of the quartz resonator is generally much higher than the frequency of the environmental noise, the sensor can maintain a wide bandwidth even when used with a filter in a differential method. Therefore this type of sensor can be used in an environment with a noisy background and in applications requiring a fast response.

This paper deals with the application of a quartz resonator to a force sensor built into an active antenna for tactile recognition of the environment, and confirms that a quartz resonator is useful as a sensor to acquire information about the contact.

2. ANTENNA WITH BUILT-IN FORCE SENSOR USING QUARTZ RESONATORS

2.1 Structure of experimental antenna

An insect antenna is flexible, and a flexible antenna gives more information than rigid antenna, but this requires a more complicated procedure than a rigid antenna. The purpose in this study is to confirm that a quartz resonator can function as a sensor for an active antenna. Accordingly,

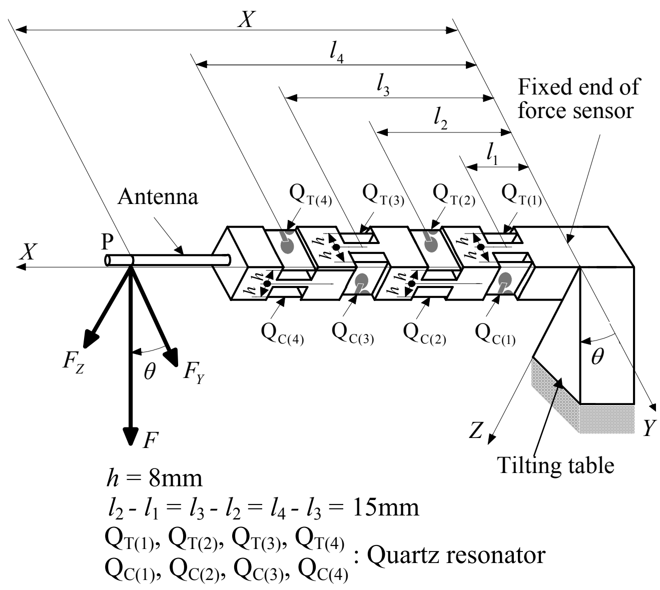

Fig. 1 Outline of experimental antenna with force sensor using four pairs of quartz resonators

in this work we used a rigid antenna to carry out recognition of an environment.

Fig. 1 shows an outline of an experimental antenna with a built-in force sensor using four pairs of quartz resonators ($Q_{C(1)}$, $Q_{T(1)}$) ~ ($Q_{C(4)}$, $Q_{T(4)}$) glued to a machined rectangular duralumin bar. The antenna made of a cylindrical stainless steel rod, 6 mm in diameter and 150 mm in length, was fixed to the tip of the force sensor. The differential method [4] was applied to reduce the influence of any external disturbance. Four pairs of quartz resonators were used to detect two components of contact force and contact position, and to ensure that the function would be fulfilled, even if one pair of the resonators was damaged [5]. Each quartz resonator is denoted by the symbol Q, with the subscripts $_{(1)}$ ~ $_{(4)}$ attached to define the resonator's position from the fixed end of the force sensor. The subscript $_T$ or $_C$ is also attached to the symbol to distinguish the two quartz resonators in each pair. The position of each pair of resonators from the fixed end of the force sensor is denoted by l_1 ~ l_4 and the distance between each resonator and the neutral axis of the bar is denoted by h. AT-cut quartz resonators that were 0.17 mm in thickness, 8 mm in width and 10 mm in length were used. Eight grooves were machined by spark erosion at symmetrical positions relative to the neutral axis of the machined bar with dimensions of 18 mm × 18 mm × 80 mm. The grooves were 0.2 mm in width and 1 mm in depth. Both ends of each quartz resonator were inserted into the grooves and glued to the bar with cyano-acrylate adhesive. The fundamental frequency was 10 ± 0.05 MHz, and the mode of vibration was a thickness shear mode. A contact force applied on the antenna was applied at longitudinal direction of each quartz resonator. The direction was at 35° ± 1° to the electrical-axis of the quartz resonator, where the force sensitivity is independent of temperature [6].

2.2 Principles of detecting contact force and position

When the antenna contacts with its environment, the contact position and two components of the contact force can be determined from the output of the force sensor. The X-axis lies along the major axis of the antenna. The Y-axis is in the direction perpendicular to the principal planes of the first and the third pairs of quartz resonators from the fixed end of the sensor, while the Z-axis is in the direction perpendicular to the principal planes of the second and the fourth pairs. We chose the origin to be at the fixed end of the sensor. Referring to Fig. 1, a force F acts at point P at an angle of θ to the Y axis in the Y–Z plane. F_Y and F_Z are the components of F in the Y and Z directions, respectively. X is the X coordinate of the point P. The difference in the frequency shifts for each pair ($Q_{C(i)}$, $Q_{T(i)}$) is expressed as $Out_{(i)}$ (i=1~4). By considering that the resonant frequencies of the resonators were in the range of 10 ± 0.05 MHz and that the four pairs are located at even intervals, then two components of the contact force F_Y, F_Z and the contact position X are given by [5]

$$F_Y = k_1 \left\{ Out_{(1)} - Out_{(3)} \right\} \tag{1}$$

$$= k_2 \left\{ \frac{Out_{(3)} \left(Out_{(2)} - Out_{(4)} \right)}{Out_{(2)} + Out_{(4)}} \right\} \tag{2}$$

$$= k_3 \left\{ \frac{Out_{(1)} \left(Out_{(4)} - Out_{(2)} \right)}{Out_{(4)} - 3Out_{(2)}} \right\} \tag{3}$$

$$F_Z = k_4 \left\{ Out_{(2)} - Out_{(4)} \right\} \tag{4}$$

$$= k_5 \left\{ \frac{Out_{(2)} \left(Out_{(1)} - Out_{(3)} \right)}{Out_{(1)} + Out_{(3)}} \right\} \tag{5}$$

$$= k_6 \left\{ \frac{Out_{(4)} \left(Out_{(1)} - Out_{(3)} \right)}{3Out_{(3)} - Out_{(1)}} \right\} \tag{6}$$

$$X = k_7 + k_8 \left\{ \frac{Out_{(1)}}{Out_{(1)} - Out_{(3)}} \right\} \tag{7}$$

$$= k_9 + k_{10} \left\{ \frac{Out_{(2)}}{Out_{(2)} - Out_{(4)}} \right\} \tag{8}$$

where k_i (i = 1~10) is constant. It is found that F_Y and F_Z can be derived simultaneously in three ways and X can be simultaneously obtained in two ways from these equations. The contact force F and its direction are given by

$$F = \sqrt{F_Y^{\,2} + F_Z^{\,2}} \tag{9}$$

$$\theta = \tan^{-1}\left(\frac{F_Z}{F_Y} \right) \tag{10}$$

2.3 Static characteristics of experimental antenna

The antenna with the force sensor was fixed onto a tilting table as a test stand as shown in Fig. 1. A contact force F was applied to the antenna at an angle θ to the Y-axis. θ was varied over the range from -45° to 135°, and for each value of θ, the contact force F was changed in the range of 0.49 N to 2.49 N. Then for each value of F, the contact position X was changed within the range 200 mm to 300 mm. $Out_{(i)}$ was measured under each of these conditions. In Fig. 2, (a) shows the relationship between X and $Out_{(i)}$ when θ = 45° and F = 1.96 N. It is confirmed that there is a linear relationship between X and $Out_{(i)}$. (b) shows the relationship between θ and $Out_{(i)}$ when X = 250 mm and F = 1.96 N. $Out_{(2)}$ and $Out_{(4)}$ are nearly zero when θ = 0°, and $Out_{(1)}$ and $Out_{(3)}$ are nearly zero when θ = 90°. This means that crosstalk can be neglected. (c) and (d) show the relationships between F and $Out_{(i)}$ when θ = 0° and θ = 90°, demonstrating that the crosstalk can, in practice, be neglected. (e) and (f) show the relationships between F and $Out_{(i)}$ when θ = 15° and X = 250 mm, and when θ = 45° and X = 250 mm, respectively. In these figures, the symbols ×,

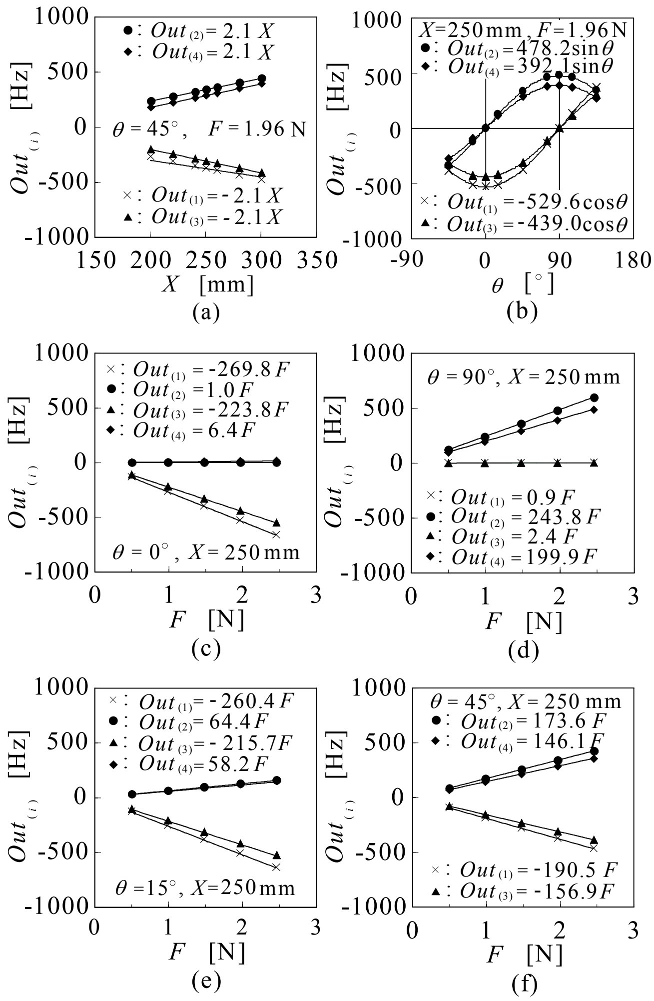

Fig. 2 Static characteristics of experimental antenna

●, ▲ and ♦ refer to the experimental values of $Out_{(1)}$, $Out_{(2)}$, $Out_{(3)}$ and $Out_{(4)}$ respectively, and the solid lines are regression lines. It is confirmed that there are linear relationships between F and $Out_{(i)}$ from Fig. 2 (c) ~ (f).

2.4. Error in measured value by experimental antenna

Fig. 3 shows the errors in the measured values which consist of the bias and the dispersion. Symbol ● shows the error, which is the difference between the real value and the measured value. The measured value of F_Y, F_Z and X were derived by substituting measured values of $Out_{(i)}$ for equations (1) ~ (8). In each figure of Fig. 3, the vertical axis shows the error ε_i, for i = 1 ~ 8, which are given by

$$\varepsilon_1 = k_1 \left\{ Out_{(1)} - Out_{(3)} \right\} - F_Y \tag{11}$$

$$\varepsilon_2 = k_2 \left\{ \frac{Out_{(3)} \left(Out_{(2)} - Out_{(4)} \right)}{Out_{(2)} + Out_{(4)}} \right\} - F_Y \tag{12}$$

$$\varepsilon_3 = k_3 \left\{ \frac{Out_{(1)} \left(Out_{(4)} - Out_{(2)} \right)}{Out_{(4)} - 3Out_{(2)}} \right\} - F_Y \tag{13}$$

$$\varepsilon_4 = k_4 \left\{ Out_{(2)} - Out_{(4)} \right\} - F_Z \tag{14}$$

$$\varepsilon_5 = k_5 \left\{ \frac{Out_{(2)} \left(Out_{(1)} - Out_{(3)} \right)}{Out_{(1)} + Out_{(3)}} \right\} - F_Z \tag{15}$$

$$\varepsilon_6 = k_6 \left\{ \frac{Out_{(4)} \left(Out_{(1)} - Out_{(3)} \right)}{3Out_{(3)} - 3Out_{(1)}} \right\} - F_Z \tag{16}$$

$$\varepsilon_7 = k_7 + k_8 \left\{ \frac{Out_{(1)}}{Out_{(1)} - Out_{(3)}} \right\} - X \tag{17}$$

$$\varepsilon_8 = k_9 + k_{10} \left\{ \frac{Out_{(2)}}{Out_{(2)} - Out_{(4)}} \right\} - X \tag{18}$$

and the horizontal axis shows the real value. δ_i expresses the bias, which is the difference between the real value and the sample mean of ε_i, and μ_i is the standard deviation of ε_i, which gives the dispersion of the measured values. Since the bias can be compensated, the dispersion accounts for the greater portion of the error. In this case, the error of the measured values of F_Y and F_Z is smaller than 2 % when maximum value of the contact force is 2 N ~ 3 N. And the error of the measured values of X is smaller than 3 mm. It is

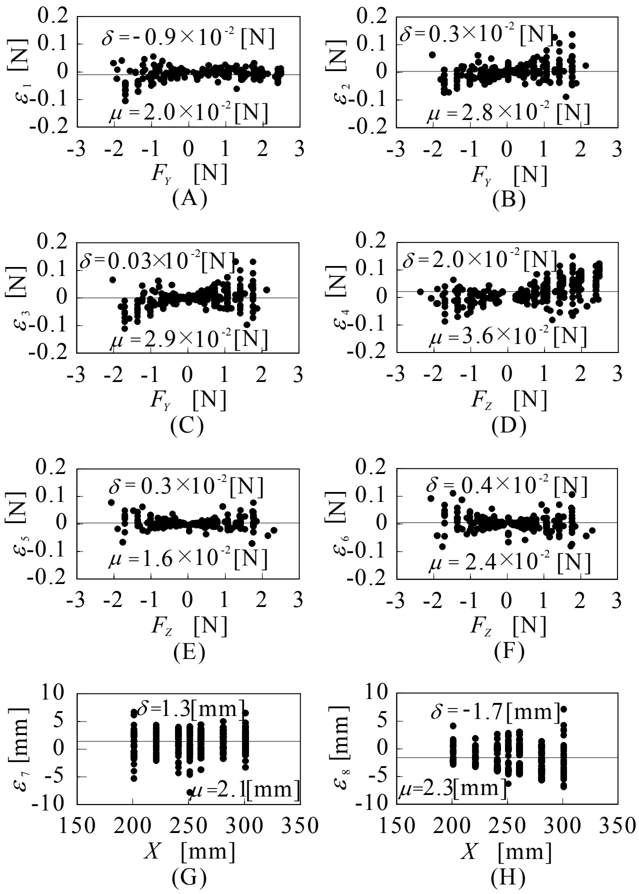

Fig. 3 Errors in measured values by experimental antenna

found that the experimental antenna fulfils its function because the errors of measured values are sufficiently low.

3. RECOGNITION OF ENVIRONMENT BY ACTIVE ANTENNA

3.1. Active antenna system for recognizing environment

Fig. 4 shows an outline of the experimental sensing system called "active antenna" in this paper. The active antenna consists of the antenna and the force sensor mentioned in the previous chapter, a vehicle and units to drive the antenna. The vehicle carried the antenna and moved it about as it searched the environment. The antenna could traverse an angle of 180° in the horizontal plane and could span 168 mm in the vertical direction by using the driving units. The antenna collided with objects in the environment as a result of this motion. The force sensor then detected the contact position and two components of the contact force. Consequently, features of the environment were recognized from the information on the contact. The antenna was linked to the vehicle such that the principal planes of all the quartz resonators were inclined at 45° to the vertical direction. Consequently, all the pairs of quartz resonators had almost the same sensitivity with respect to a horizontal force and a vertical force. The location of the vehicle was measured by a camera fixed to the ceiling.

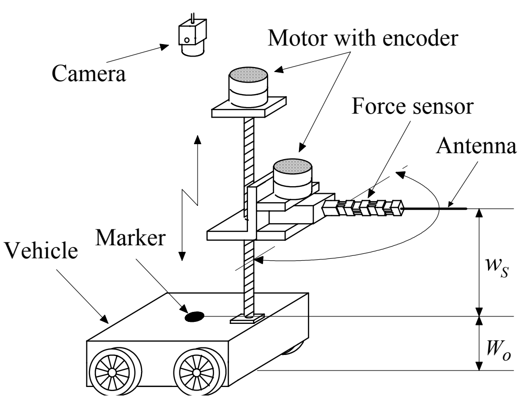

Fig. 4 Outline of active antenna system

3.1. Principles of detecting contact position

Fig. 5 shows details of the coordinate systems used in this study. The Cartesian coordinate system fixed to the floor is denoted by *O-UVW*. And one fixed to the vehicle is denoted by *o-uvw*. The origin of *o-uvw* system is denoted by (U_o, V_o, W_o) in the *O-UVW* system. *S* means the connection point between the antenna and the vehicle, and is the rotation centre of the antenna in the horizontal plane. The coordinate of the point *S* in *o-uvw* system is denoted by (u_S, v_S, w_S). The distance between the point *S* and the contact point *P* is denoted by *X*. α means the angle between *U*-axis and *u*-axis. β means the angle between the principal axis of the antenna and *u*-axis, which is the swing angle of the antenna. *d* means diameter of the antenna. β and w_S were detected from the output of an encoder built into each of the two motors. Coordinates (U_o, V_o), which are origin of *o-uvw* system, were determined by detecting the marker on the vehicle by the camera on the ceiling. The coordinates of the contact point P in *o-uvw* and *O-UVW* systems are denoted by (u_P, v_P, w_P) and (U_P, V_P, W_P), respectively. These are given by

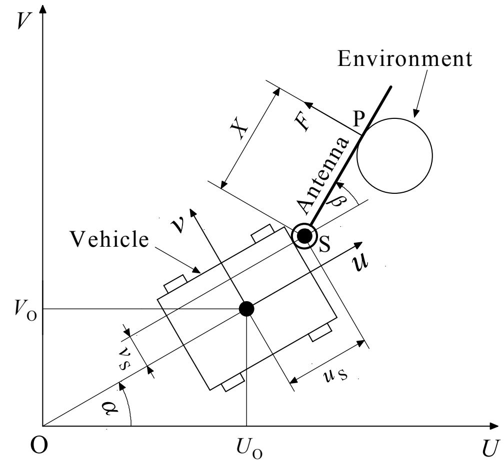

Fig. 5 Coordinate systems for active antenna

$$\left.\begin{aligned} u_P &= u_S + X\cos\beta + \frac{1}{2}d\sin\left(\theta - \frac{\pi}{4}\right)\sin\beta \\ v_P &= v_S + X\sin\beta - \frac{1}{2}d\sin\left(\theta - \frac{\pi}{4}\right)\cos\beta \\ w_P &= w_S + \frac{1}{2}d\cos\left(\theta - \frac{\pi}{4}\right) \end{aligned}\right\} \tag{19}$$

$$\left.\begin{aligned} U_P &= u_P\cos\alpha - v_P\sin\alpha + U_o \\ V_P &= u_P\sin\alpha + v_P\cos\alpha + V_o \\ W_P &= w_P + W_o \end{aligned}\right\} \tag{20}$$

where θ is a contact force direction as shown in Fig. 1.

3.2. Recognition of two-dimensional shape

The active antenna could recognize the two-dimensional shape of an environment. In this case, the vehicle was fixed to the floor. The antenna translated from the lower end to the upper end of the vehicle every 1mm, and swung in a horizontal plane at each vertical position. When the antenna ran into part of its environment, the force sensor built into the antenna detected the contact position. The overall shape of the environment was reconstructed from the set of data on the contact positions. When $Out_{(1)}$ or $Out_{(2)}$ changed by 20 Hz (corresponds to about 0.01 N), it was judged that the antenna came into contact with an object in the environment.

Fig. 6 (a) shows the result of recognizing both sides of a rectangular plate whose width and height is 220mm and 130 mm, respectively. The symbol • means the measured value, and the solid line shows actual shape of the object. Bias δ (accuracy) of measured values of left-hand sides is 2.2 mm, and standard deviation μ of residuals (precision) is 1.4 mm. Those of right-hand side are 4.7 mm and 1.5 mm, respectively.

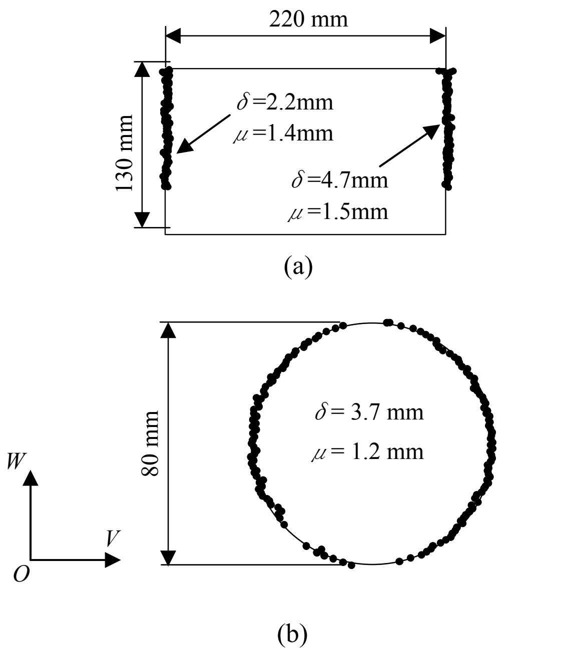

Fig.6 Result of recognizing (a) both sides of a rectangular plate and (b) outer periphery of circular plate

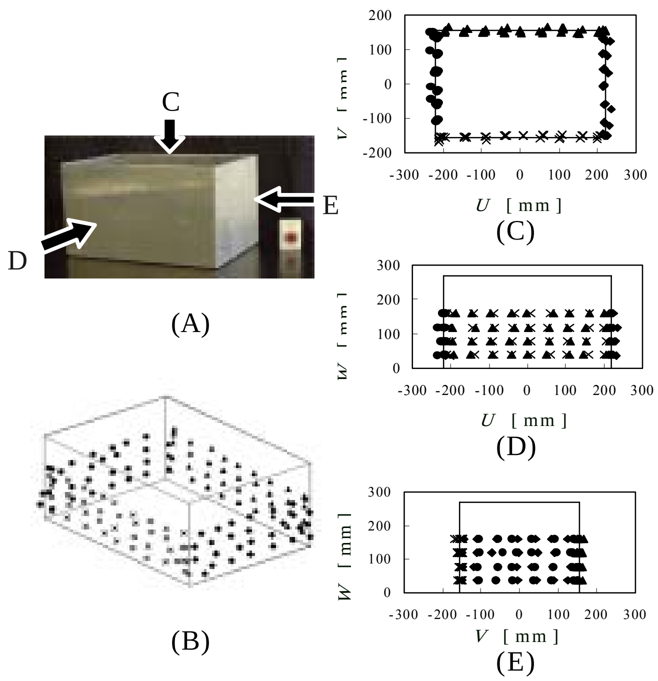

Fig.7 Result of recognizing four side faces of rectangular parallelepiped

Fig. 6 (b) shows the result of recognizing the outer periphery of a circular plate whose diameter is 80 mm. Bias (accuracy) of centre of the circular plate derived from measured values of the outer periphery is 3.7 mm, and standard deviation of residuals (precision) is 1.2 mm.

3.3. Recognition of three-dimensional shape

The vehicle carrying the antenna moved about on the floor, and the antenna on the vehicle performed the same set of actions that were used for two-dimensional recognition at each position on the floor. Fig. 7 shows the result of recognizing the four side faces of a rectangular parallelepiped (440 mm × 310 mm × 270 mm). (A) shows photograph of the object. (B) shows the single view drawing of measured values. (C), (D) and (E) are projection drawings to the planes perpendicular to C-, D- and E-directions shown in (A), respectively. Symbols ×, ●, ♦ and ▲ shows measured values, and the solid line shows actual shape of the object. Biases (accuracy) of measured values of four side faces are 1.8 mm, 0.7 mm, -1.2 mm and 0.4 mm, respectively. And standard deviations of residuals (precision) are 5.0 mm, 6.8 mm, 5.5 mm and 5.8 mm, respectively. The standard deviations are large compared with in the case of two-dimension shape. It is regarded that this caused by special resolution (5.8 mm) of the camera for detecting the location of the vehicle.

4. CONCLUSIONS

Firstly, an experimental antenna with four pairs of quartz resonators was proposed for use in recognition of environment. Secondly, the prototype of a sensing system was proposed, which in this paper we call “active antenna”. Finally, the results of using the active antenna to recognize various environments were presented. It was verified that a quartz resonator is useful as a force sensor to be built into an active antenna from the aforementioned results.

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