A PILOT STUDY ON ULTRASONIC SENSOR-BASED MEASUREMENT OF HEAD MOVEMENT

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Abstract*-In the present paper, we propose a high-performance, ultrasonic sensor-based head movement detection system, which can be easily applied as an eye tracking device by rotating a mirror set in front of a video camera in a head-free video-based eye-gaze detection system. We propose a simple distance measurement method that uses an A-D converter and an envelope detection method. Experimental results indicate small standard deviations of less than 0.9 mm when the distance between transmitter and receiver is within the range of 40 - 80 cm. In addition, we arranged three transmitters on the apices of a triangle to simulate the head of the user. The receivers were arranged on the apices of a larger triangle. The coordinates of each transmitter were determined using the measured distances from the transmitter to the three receivers. The center of gravity of the three transmitters and the normal vector of the plane that includes the three transmitters were calculated based on the estimated coordinates of the three transmitters. The results indicate sufficiently high precision and measuring frequency for our purpose. The proposed method would be useful for adjusting the focus of a zoom lens to the eye, as well as adjusting the direction of the mirror to the eye.

***keywords* - distance measurement, tracking, eye-gaze detection, man-machine interface**

I. INTRODUCTION

We are developing a head-free video-based eye gaze detection system for use as a man-machine interface. The system involves the use of a video camera that is placed 50 or 60 cm from the user's eye [1]. Since the eye's image goes out of the camera frame as a result of large head movements, we have proposed methods by which a camera [2] or a mirror set in front of the camera [3] is rotated, so that the eye image is maintained in the center of the camera frame. However, once the eye image was lost from the frame, it must have been searched by their rotation [4]. This searching needed a significant period of time. Therefore, an improved method for tracking the eye in real time is desired.

It can be assumed that the eyeball rotation center is fixed in the head of a user. If the three transmitters are fixed on the user's head, the positional relationship between the eyeball rotation center and the transmitters is also fixed. Once the relationship is determined, the position of the eyeball rotation center in space can be estimated in real time using the positions of the three transmitters, even if the head moves and rotates. This enables the direction of the camera optic axis to coincide with the eyeball rotation center in space. As a result, acquisition of the eye image is always possible. The present paper proposes a method by which to determine the direction and position of the head in real time using ultrasonic sensors.

In order to measure the direction and position of the head in space, at least three transmitters are fixed on the head and each of these positions must estimated. This requires at least three receives. In the case of using only one transmitter, the phase difference method [5] can be used. However, the simultaneous and continuous ultrasound transmission from three transmitters must cause the algorithm of positional determination to be very complex. Accordingly, in the present study, the conventional time-of-flight (*ToF*, for instance, [6]) is useful because the three transmitters can easily send the ultrasonic wave in separate time intervals: a time-sliced *ToF* method. In general, however, distance measurement using the *ToF* method is inaccurate: the accuracy of the wavelength of the ultrasound (8.8 mm at 40 kHz). Recently, more accurate method based on the *ToF* has been proposed [7], which utilizes the entire received signal (correlation function and phase) rather than the signal at onset. However, upon testing this method on an ultrasonic sensor, which was considered to be best suitable for our purpose, the total oscillating duration of the received signal was found to fluctuate greatly, thereby reducing the accuracy of the distance measurement. Therefore, we propose a new envelope detection method for accurate distance measurement.

II. PRINCIPLE OF HEAD MEMOVEMENT MEASUREMENT USING ULTRASONIC SENSORS

Suppose that three ultrasonic transmitters, S_0, S_1, and S_2, are attached to the head (Figs. 1(a) and (c))

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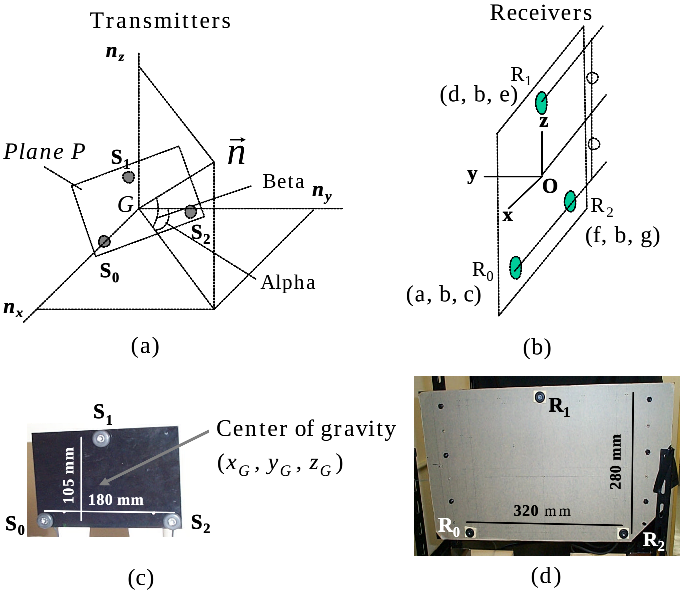

Fig. 1. (c) and (d) Arrangements of three transmitters and three receivers, and definitions of (b) the coordinate system and (a) angles of the plane including the three transmitters.

and that the ultrasounds sent from them are received with three receivers, R_0, R_1, and R_3, attached around the computer screen. The distances between each transmitter and each receiver are measured using an ultrasound time-of-fight method.

The coordinate system is set as shown in Fig. 1(b). The coordinates of R_0, R_1, and R_2 are known as (a, b, c), (d, b, e), (f, b, g). If the distances from S_0 to R_0, R_1, and R_3 are measured as L_0, L_1, and L_2, S_0 exists on the intersection of the three spherical surfaces having the centers of R_0, R_1, and R_2, and having the radiuses of L_0, L_1, and L_2, respectively. Therefore, the coordinates of S_0 is determined by solving the simultaneous equations of the three spherical surfaces. The coordinates of the remaining two transmitters, S_1 and S_2, are determined in the same way.

Assume a plane, *P*, including all of S_0, S_1, and S_2 (Fig. 1(a)). The components of the normal vector of *P*, are determined as (n_X, n_Y, n_Z). From these, the horizontal and vertical angles (Alpha, Beta) of the normal vector of *P* are obtained. These angles and the center of gravity of the three transmitters give the direction and position of the head, respectively.

III. MEASUREMENT OF DISTANCE BETWEEN A TRANSMITTER AND A RECEIVER

A. Transmitting and Receiving

Small and lightweight (diameter 9.9 mm, 2 grams) ultrasonic sensors having and a weak directivity (80 deg) were used in the preset study. The rectangular pulse train signal sent to the transmitters was generated from an oscillator circuit (39.0625 kHz). The signal was indirectly gated by a personal computer (Celeron, 800 MHz) through a digital output terminal on an A-D converter. The gate opened synchronously with the earliest raising of the rectangular signal after the order from the computer, and then automatically shut after sending out just four periods of the rectangular signal to the transmitters. Simultaneously with gate opening, 1200-point A-D conversion of the signal obtained from the receiver automatically began after 350-point delay by using a trigger delay start function of the converter. The sample rate was 3.2μs, corresponding to 8 samples per period of the ultrasound. Due to the trigger delay of 350 sample points, it could measure distances farther than approximately 385 cm.

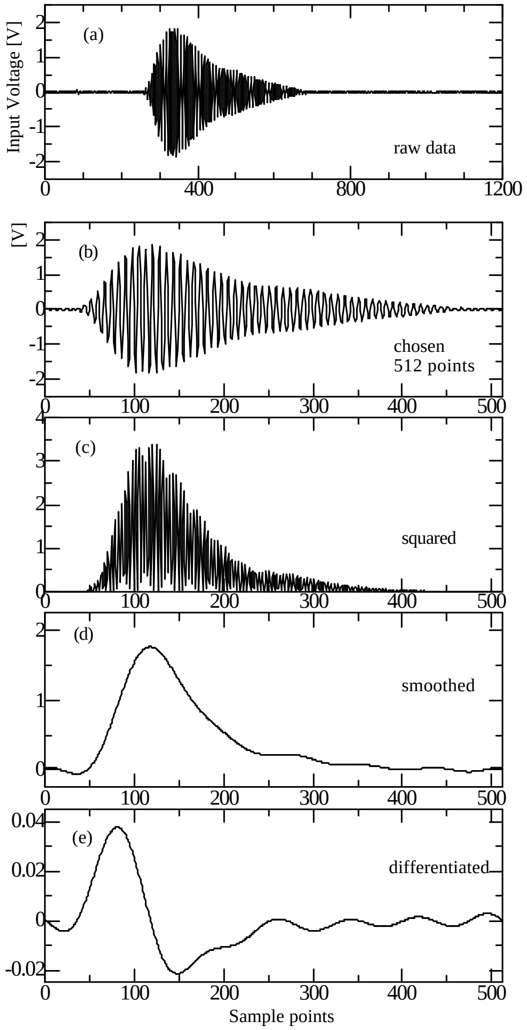

Fig. 2. Analysis method of received signal.

B. Calculation of Distance

Fig. 2(a) shows a typical 1200-point signal that was sampled by the A-D converter. First, 512 points including the signal were chosen for the following analyses (Fig. 2(b)). Second, the 512 points were squared (Fig. 2(c)). Third, smoothing in the frequency domain was executed (Fig. 2(d)). Fourth, the smoothed signal was differentiated (Fig. 2(e)). The temporal point where the value that crossed zero level was detected as T_F. The resolution of T_F coincides with the A-D sampling interval (3.2μs); this corresponding to approximately 1.1 mm. To increase the resolution, fifth, in the differentiated signal, the previous and subsequent points of zero crossing were interpolated with a direct line. The time when the line crossed zero level was calculated and was used as the ultrasonic reaching time, i.e., *ToF*. The measured distance is obtained by multiplying *ToF* by the sound velocity. The velocity was compensated by temperature.

C. Calibration and Stability of Distance

The measured distances did not coincide with the actual distances. Calibration between them was executed as follows: A transmitter and a receiver were arranged face-to-face. 500 times of distance measurements were done for each distance from approximately 400 mm to 800 mm. The SD of the measured distance showed the values between 0.4 mm and 0.9 mm, tending to increase as the actual distance. The equation of the regression line was calculated. The correlation coefficient was r=0.99998. Based on the equation of the regression line, the equation used to transform from the measured distance, D_M, into the estimated distance, D_E, is as follows:

$$D_E = 1.004980 D_M - 18.0275 \text{ [mm]} \qquad (1)$$

Later, this equation is used for compensation of distances.

IV. MEASUREMENTS OF POSITION AND DIRECTION BY 3 TRANSMITTERS AND 3 RECEIVERS

The three transmitters and three receivers were attached to a small plate (Fig. 1(c)) and a larger plate (Fig. 1(d)), respectively. The three transmitters sequentially sent an ultrasonic wave. Every transmission, the signals from the three receivers (R_0, R_1, and R_2) were each A-D converted every 3.2μs, and then the three distances (L_0, L_1, and L_2) were estimated. Next, the coordinates of position in space of the three transmitters were estimated. Finally, the center of gravity of the transmitters (x_G, y_G, z_G) and the direction of the normal vector of plane *P* (Alpha, Beta) were calculated. These parameters were obtained 100 times/sec.

Static experiment was performed. The plate having the three transmitters was placed at several locations. Figs. 3(a)-(c) show the relationships between the actual and estimated positions for x_G, y_G, and z_G, respectively. In each figure, the coordinate of interest is variable and the other two coordinates are con-

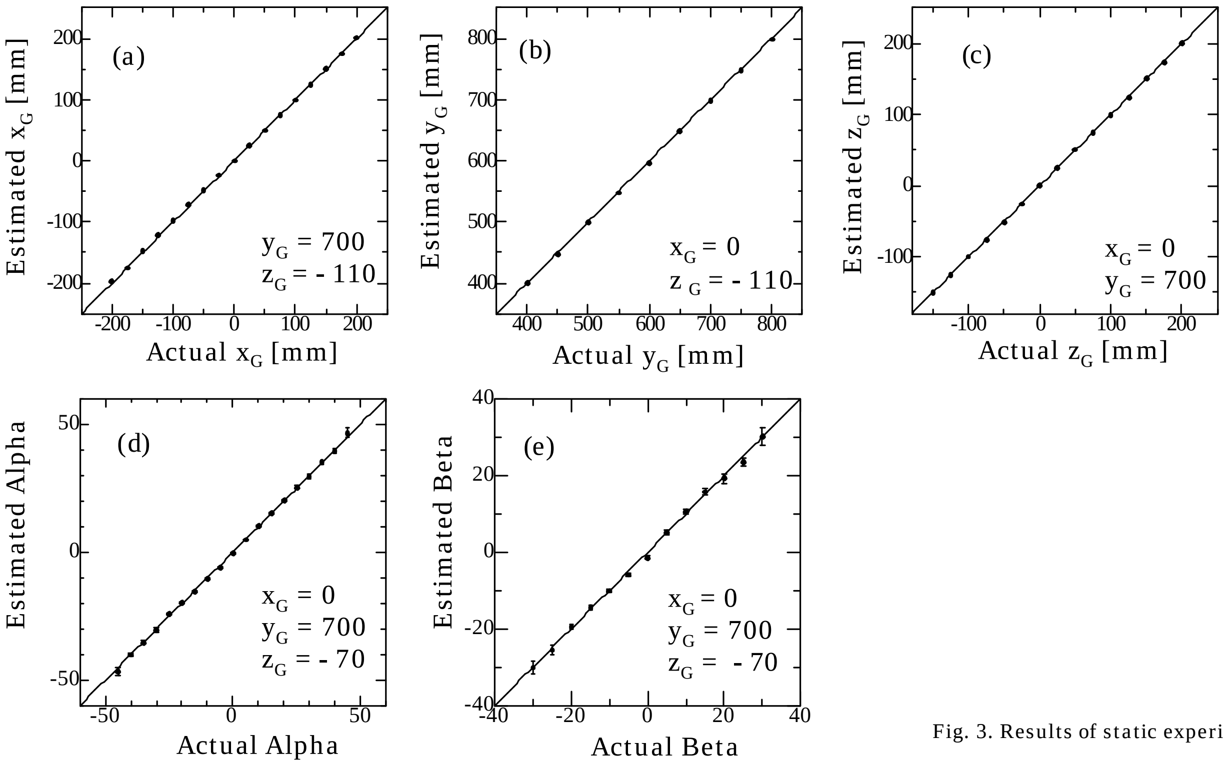

Fig. 3. Results of static experiment.

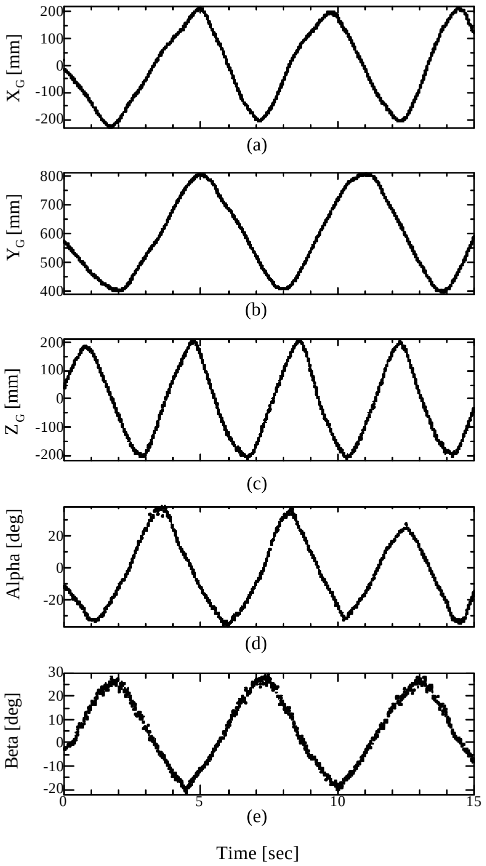

Fig. 4. Results of dynamic experiment.

stant. The figures show strong linear relationships, slopes of approximately 1.0 and small SDs. The averages of the SDs for x_G, y_G, and z_G were 1.463 mm, 0.315 mm, and 1.827 mm, respectively. Figs. 3(d) and (e) show the relationships between the actual and estimated positions for Alpha and Beta, respectively. The average SD of Alpha was 0.46 deg for an angle range of ±40 deg. Those of Beta was 0.64 deg and 0.93 deg for angle range of ±20 deg and ±30 deg, respectively.

Finally, dynamic experiments were performed. The transmitter plate was moved by hand. As a result, a slight trembling of the plate occurred. Each panel in Fig. 4 indicates the results for the case in which one of he five parameters was varied. The other parameters were set to have approximately the same value as that for the static experiments (Fig. 3). These results show that the data was relatively smooth.

V. DISCUSSION

The results in Figs. 3 and 4 indicated that the proposed method for measuring the position and direction of the head has sufficiently high accuracy to direct the camera's optic axis to the eye over a wide spatial range.

By using the standard computer, one hundred measurements per second were materialized. The highly frequent measurement would make it easy to track the eye by open-loop mirror control with almost no time delay. It took 10 ms for calculation of the distances from the signals obtained from the three receivers. Using a faster computer can shorten the time, whose limitation is determined by the measurable distance range (the period of A-D conversion). In the present setting, the farthest measurable distance was approximately 1100 mm. For this condition, the limitation is approximately 5 ms, corresponding to 200 measurements per second. This frequency of measurement would produce higher accuracy because the moving average method can be used with negligible delay.

VI. CONCLUSION

In this paper, we proposed a high performance, ultrasonic sensor-based head movement detection system, which would be easily used for tracking the eye by a rotation mirror in a head-free eye-gaze detection system. This method would be useful for controlling the focus of the zoom lens.

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