Estimation of Absolute Positioning of Mobile Robot Using U-SAT

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Abstract. This paper proposes a new method to find an absolute position by using ultrasonic sensors. In order to evaluate the performance of U-SAT (Ultrasonic Satellite system), the autonomous navigation performance of a mobile robot is tested. Experiments were performed in both cases that the mobile robot moves to the target point using relative positioning method in conjunction with U-SAT, which is, absolute positioning methods. The performance of U-SAT is evaluated accordingly with the results of the experiments. As a result, U-SAT could be effectively used as a pseudolites or pseudo-satellites to help a mobile robot navigate intelligently and autonomously in an indoor area.

1 Introduction

In terms of obstacle avoidance and path planning, it is a very significant issue for a mobile robot to identify its positions. Research on this issue has been actively conducted. Positioning can be largely divided into relative positioning and absolute positioning. Dead reckoning (DR) is widely used as a method of relative positioning. In this method, however, positioning errors are accumulated due to wheel sliding, mechanical errors and surface roughness, making it difficult to determine an actual position as the distance gets longer [1]. For this reason, it is only difficult for relative positioning to identify the accurate position of a robot that navigates a long distance. Accordingly, it is necessary to conduct absolute positioning and correct the positions. GPS (Global Position System) is widely used for absolute positioning, but GPS is expensive and cannot properly receive satellite signals indoors, which makes its indoor application to a robot difficult. Therefore, a great deal of research is underway in order to estimate absolute positions.

In a bid to estimate absolute positions indoors, much research is being conducted using CCD cameras, infrared rays and ultrasonic waves. First of all, the method using a CCD camera is expensive and requires complex signal treatment. It is also affected by camera correction and operating conditions [2,3]. Second, the system using infrared rays can be established easily and inexpensively but the coverage area is not

K. Li et al. (Eds.): NPC 2007, LNCS 4672, pp. 143–150, 2007.

wide and its performance level is lower than the other systems. In addition, it is greatly influenced by light [4]. Lastly, ultrasonic sensors are inexpensive and easy to use. They also consume less electricity than laser sensors or vision sensors and their signal handling devices are relatively simple.

This paper adopted a method in which the receiving part of an ultrasonic sensor receives ultrasonic waves from the ultrasonic transmitters located at a fixed position and estimates an absolute position [5,6]. In addition, this study proposed a method with a high degree of precision in the measurement of distances which separates the ultrasonic receiver and transmitter [7]. Based on this, a U-SAT (Ultrasonic Satellite system) of excellent performance has been developed to estimate a three-dimensional absolute position. Also, DR, which has been widely used for relative positioning, and a U-SAT have applied to a mobile robot to evaluate positioning and autonomous navigation performance.

2 Absolute Positioning of U-SAT

Distance measurement using ultrasonic waves makes use of the transmission speed and time information of ultrasonic waves. The time taken for the transmission of ultrasonic waves through air is called T.O.F. (Time of Flight), and it is defined as the difference between the time of transmission of the signal (t_t) and the time of its receipt (t_r). The distance (d) measured by ultrasonic waves can be expressed as follows:

$$d = c \times T.O.F \tag{1}$$

where, d_0 represents the distance offset caused by the vibrating plate position errors of the transmitter-receiver part, and c indicates the ultrasonic wave speed and is defined as follows for centigrade temperature T.

$$c = 331.5 + 0.60714T \tag{2}$$

Therefore, influence of temperature should be considered when measuring distances using ultrasonic waves.

In general, T.O.F. is determined by the time needed for the size of an ultrasonic signal to reach a certain threshold level after the ultrasonic receiver has received the ultrasonic signal. In this distance measuring method, however, it is difficult to determine a threshold of a proper size due to the influences of the media in the air, temperature, attenuation caused by a frequency increase and the absorption of ultrasonic waves by objects. The degree of precision decreases due to the sensitivity to noise. Therefore, this paper adopted T.O.F. measurement using the period detecting method [7]. With an increase in T.O.F., the amplitude of a transmitted signal is attenuated, with its period remains unchanged. Accordingly, if detection is made based on the period, the precision of distance measurement can be enhanced irrespective of the amplitude attenuation.

U-SAT can be composed as shown in Fig. 1. MURATA MA40BR/S of 40 kHz was used for the ultrasonic transmitter-receiver sensor. The ultrasonic transmitter discharges ultrasonic waves of 40 kHz as soon as it receives wire-carried synchronized signals from a synchronized RF-signal transmitter. At the same time, the synchronized RF-signal transmitter sends synchronized signals to the ultrasonic wave receiver, which calculates T.O.F. with the use of the time difference between the synchronized RF signals and the ultrasonic waves received. Using the T.O.F., the receiver also calculates the distance between the ultrasonic transmitter and receiver. With the outcome, the receiver can obtain its own three-dimensional coordinates. This is similar to the basic principles of GPS. In the case of GPS, a satellite transmits its starting signal and position information but U-SAT searches its starting point of time with synchronized RF-signals. The synchronized RF-signal transmitter is positioned together with transmitter #1. Synchronized signals are transmitted to transmitters #2, #3 and #4 by cable at certain intervals, controlling the transmission of ultrasonic waves one after another. Even though there are several receivers, they do not interfere with each other and can secure their own positions independently.

Fig. 2 shows a time diagram in which an ultrasonic receiver receives ultrasonic waves by synchronized RF signals. Based on the synchronized RF-signals, the ultrasonic receiver calculates T.O.F. of ultrasonic waves received from an ultrasonic transmitter, and it also calculates d1, d2, d3, and d4, which are the distances between the ultrasonic transmitter and receiver. After receiving synchronized RF-signals from an ultrasonic transmitter, the ultrasonic receiver should wait 100ms to receive next ultrasonic signal. Thus ultrasonic waves are transmitted at certain intervals to prevent interference between transmitters and reduce the influences of reflective waves.

Next, the positions of the ultrasonic receivers (x, y, z) can be expressed as in Eq (3) from the four fixed positions of the ultrasonic waves (x_i, y_i, z_i) and the distances between transmitters and receivers d_i $(i = 1,2,3,4)$

$$\begin{aligned}(x_1 - x_2)x + (y_1 - y_2)y + (z_1 - z_2)z &= \alpha \\ (x_2 - x_3)x + (y_2 - y_3)y + (z_2 - z_3)z &= \beta \\ (x_3 - x_4)x + (y_3 - y_4)y + (z_3 - z_4)z &= \gamma\end{aligned} \tag{3}$$

This can be changed to a matrix operation and is expressed as follows.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = A^{-1} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \tag{4}$$

$$\text{Where, } A = \begin{bmatrix} (x_1 - x_2) & (y_1 - y_2) & (z_1 - z_2) \\ (x_2 - x_3) & (y_2 - y_3) & (z_2 - z_3) \\ (x_3 - x_4) & (y_3 - y_4) & (z_3 - z_4) \end{bmatrix},$$

$$\alpha = \frac{1}{2}\{(x_1^2 - x_2^2 + y_1^2 - y_2^2 + z_1^2 - z_2^2) - (d_1^2 - d_2^2)\},$$

$$\beta = \frac{1}{2}\{(x_2^2 - x_3^2 + y_2^2 - y_3^2 + z_2^2 - z_3^2) - (d_2^2 - d_3^2)\},$$

$$\gamma = \frac{1}{2}\{(x_3^2 - x_4^2 + y_3^2 - y_4^2 + z_3^2 - z_4^2) - (d_3^2 - d_4^2)\}.$$

In Eq (4), if $\det A \neq 0$, (x, y, z) has a singular solution, making it possible to obtain three-dimensional coordinates in space.

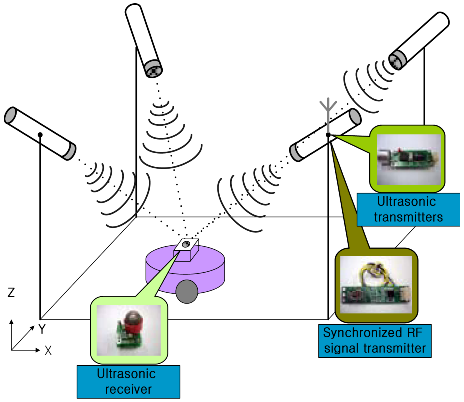

Fig. 1. Configuration of U-SAT

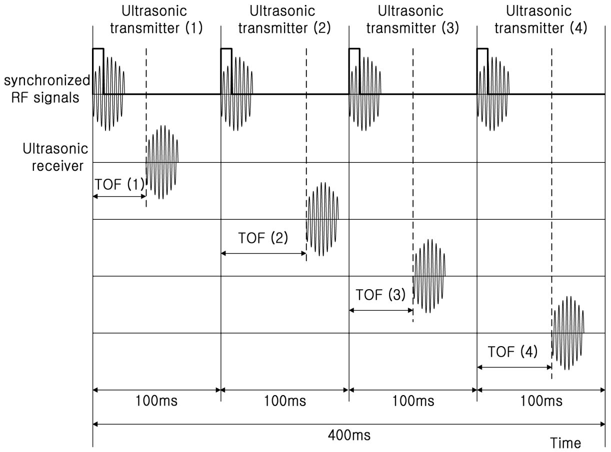

Fig. 2. Timing Diagram

3 Autonomous Navigation Algorithm of a Mobile Robot

The posture of a mobile robot driving on a two-dimensional plane can be shown as follows.

$$p = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \tag{5}$$

where, θ represents the heading angle indicated counterclockwise from axis X. The kinematics of a mobile robot can be expressed by Jacobean matrix J as follows [8].

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \dot{p} = Jq = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} q \ , \ q = \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{6}$$

where, v and ω represent the linear velocity and rotational velocity, respectively.

A mobile robot control system uses two positions of reference position $p_r = [x_r, y_r, \theta_r]^T$ and the current position $p_c = [x_c, y_c, \theta_c]^T$. In Fig. 3, the reference position is the position targeted by the mobile robot, and the current position indicates the position in which the mobile robot is actually located. When a position error between the reference position p_r and the current position p_c is defined as p_e , it can be expressed as follows.

$$p_e = \begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{bmatrix} (p_r - p_c) = T_e (p_r - p_c) \tag{7}$$

$$\text{Where, } T_e = \begin{bmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

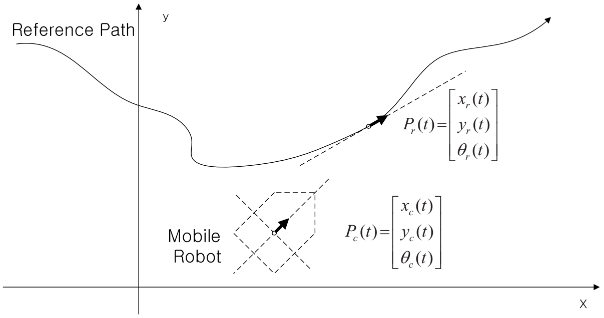

Fig. 3. Reference and current postures

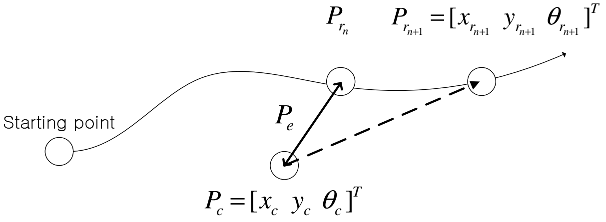

Fig. 4. Position estimation of a mobile robot

As shown in Fig. 4, when a position error p_e occurs between the current position p_c and the reference position p_{r_n}, it is difficult for a mobile robot to navigate to the accurate next reference position $p_{r_{n+1}}$ in the case of the autonomous navigation algorithm of a mobile robot. Therefore, it is necessary to calculate p_e after accurately measuring the current position p_c, estimated with U-SAT. When the error of the measured heading angle is above $\pm 3°$, it is necessary to reestablish the heading angle and the distance to the next reference position $p_{r_{n+1}}$. The robot should be driven along the trajectory in this way so that the errors may not be accumulated. Changing distances and heading angles can be calculated with the following equation.

$$\begin{aligned} D_p &= \sqrt{(x_{r_{n+1}} - x_c)^2 + (y_{r_{n+1}} - y_c)^2}, \\ \theta_p &= \theta_{r_{n+1}} - \theta_c \end{aligned} \tag{8}$$

where, D_p represents modified distance information, and θ_p indicates modified heading angle information.

4 Positioning Performance Experiment of a Mobile Robot

Fig. 5 shows the mobile robot used in this experiment. The right and left wheels of the mobile robot are driven by a stepping motor, and they rotate at 1.8 degrees per pulse. The movement and turn of the mobile robot are controlled by the two wheels. The width of the mobile robot is 100.8mm and the radius of the wheels is 25.6mm. Two ultrasonic receivers are attached to the front and back of the robot to estimate the positions and heading angles of the robot. Through a Bluetooth modem, data are transmitted to the remote control part and the robot receives wheel driving control

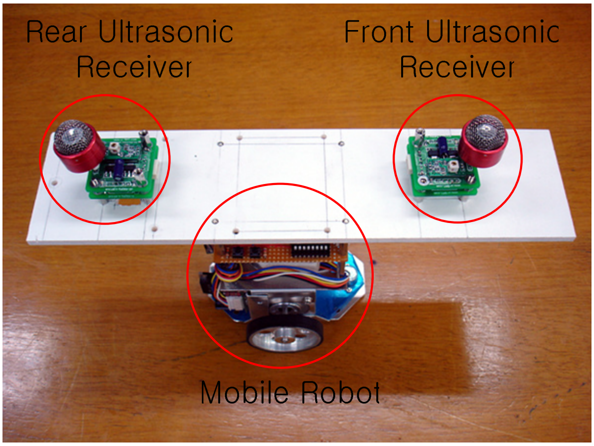

Fig. 5. Configuration of a mobile robot

orders. Using the algorithm proposed in the above and the positions and heading angles received from the ultrasonic receiver, the remote control part controls the robot. The remote control part was programmed using Visual C++.

Next, the positioning performance of the mobile robot is evaluated with use of the autonomous navigation algorithm suggested above. First, only DR was used to examine the state at the time when the mobile robot moved to the desired trajectory. Then, the autonomous navigation algorithm using U-SAT was applied to the mobile robot to evaluate the performance when the robot moved to the desired trajectory. In evaluating the positioning performance, the maximum speed was set at 300mm/s. For the experiment, four ultrasonic transmitters were installed to the rectangular satellites with a size of 7000x5000 mm attached to the ceiling.

Fig. 6 shows the results of the experiment in which the mobile robot autonomously navigated counterclockwise along a rectangular trajectory with a size of 2000x1000 mm. When positioning is conducted using DR only, the accumulated errors cannot be eliminated and therefore large accumulated errors occur when the mobile robot returns to the starting point. It was found that the errors between the first starting position and the position to which the robot returned after making a round were 117mm in the X direction and minus 209mm in the Y direction. Therefore, DR alone could not reduce the errors, making it difficult to properly perform autonomous navigation. Next, it was found that when autonomous navigation was conducted by estimating the position and heading angle using U-SAT, no accumulated errors occurred, and the robot was navigating in a stable manner within the position error range of ±30 mm. Unlike the previous results, it was found that when the mobile robot arrived at the final target point, the position errors were minus 2mm in the X direction and minus 14mm in the Y direction. Accordingly, when a mobile robot is navigated with absolute position estimations using U-SAT, accumulated errors can be decreased. Such positions may also apply to obstacle avoidance and path planning, giving a higher level of flexibility for working environments.

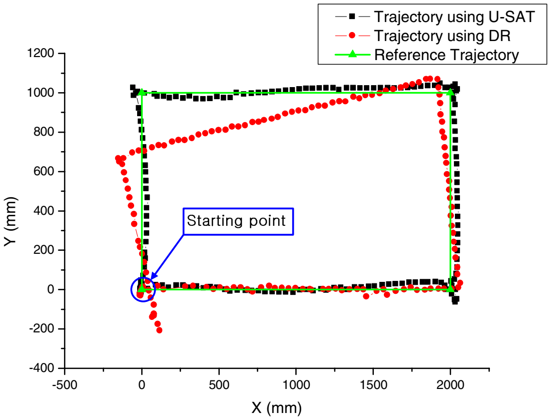

Fig. 6. Experimental result of the relative and absolute positioning performance

5 Conclusion

This paper has developed a U-SAT applicable indoors and tested the autonomous navigation performance of a mobile robot to evaluate the performance of U-SAT. To evaluate the positioning performance of a mobile robot using the proposed U-SAT, this paper examined two cases of autonomous navigation: the case in which a mobile robot conducted autonomous navigation only with relative position estimations and the case in which a mobile robot made autonomous navigation using absolute position estimations. The results showed that when relative position estimations were used, the robot could not navigate toward the desired position due to the accumulated errors but when absolute positions were estimated using U-SAT, the robot could autonomously navigate along the target trajectory in a stable manner. Therefore, the use of position estimations of U-SAT could greatly help a mobile robot navigate intelligently and autonomously. Further studies need to develop methods that can measure exact positions even when a mobile robot navigates at a faster speed.

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