A TDOA-Based Ultrasonic Absolute Localizing System of a Rail Robot in Greenhouse

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Abstract – In this paper, we present a method for localization of a rail autonomous pesticide spraying and sampling robot working in greenhouse using an absolute localization system. Design and implementation of the localization system comes from the usage of beacon systems each of which is composed of an RF single receiver and an ultrasonic transmitter. The RF single receiver gets the synchronization signal from the mobile robot, and the ultrasonic transmitter sends ultrasonic signal, thus the distance from the beacon to the ultrasonic receiver can be measured. The position of a beacon in coordinate system of robot can be calculated according to distance information from the beacons to two ultrasonic receivers which are mounted on the robot. Based on the coordinate transformation, the position of a mobile robot can be calculated from the beacon's absolute position information in the global coordinate system. Experiments demonstrate the effectiveness of the proposed method in real world applications.

Key words* – *TDOA*; *rail robot*; *absolute localization*; *active beacon*; *navigation

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1 Introduction

Robotics has obtained more and more applications in agricultural industry. Greenhouse is an important place of production for modern agriculture. Sometimes, the mobile robot runs on the elevated rail in greenhouse. The localization of traditional rail robot system almost uses relative positioning, such as dead reckoning (i.e., measuring the wheel rotation angle to compute the offset from a known starting position), which is simple, inexpensive, and easy to implement in real time. But this method brings accumulating wheel-slippage errors, so it is unsuitable for rigorous agriculture research. A substitute for relative positioning system is the absolute positioning scheme, for instance, the well-known satellite positioning system, such as Global Position System (GPS) system, in which the localization process is based on triangulation using the distance between the GPS receiver on a mobile object and three or more satellites[1]. But GPS is inaccurate for navigating mobile robots in narrow space and is not accessible in a building. So many GPS-like indoor localization systems have been developed, which consists of pseudo satellites and receivers to sense the relative position and attitude of a vehicle in a laboratory environment[2-4]. However, these navigation systems are usually too complex and expensive to be used for actual applications.

In this paper, a kind of absolute localizing system based on Time Difference of Arrival (TDOA) method is presented. The method uses the time difference of arrival of Radio Frequency (RF) and Ultrasound Signal (US) to calculate the distance between transmitter and receiver. Considering the speeds of RF approaching the speed of light, in this system, the travel time of RF signal is ignored.

In this system, an active beacon is used. The Active Beacon System (ABS) consists of a Radio Frequency (RF) receiver and an ultrasonic transmitter. In the localization system, each beacon has own unique ID. A mobile robot can select a specific beacon by sending a desired beacon ID in RF. When a beacon receives its own ID from the robot, it sends back ultrasonic wave to measure the distance from the beacon to ultrasonic receiver which are mounted on the robot based on the time of freight.

In the past GPS-like indoor localization systems, the GPS positioning algorithm is usually used[5,6]. The position of a mobile robot in a three dimensional space can be calculated basically from the distance information of three beacons which have their own absolute position information. According to the actual conditions of greenhouse, we propose a "inverted" GPS configuration with the position of a beacon calculated from the distance information be-

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tween the beacon and two or more ultrasonic receivers which are mounted on the robot. By using coordinate transformation, the position of the robot is calculated.

2 Inverted configuration localization

Most developed indoor localization systems rely on navigation beacons or landmarks which have the advantages of being economical and accurate. In proposed system, a kind of active beacon is used. The beacon consists of a Radio Frequency (RF) and an ultrasonic transmitter. The simple RF receiver module is added to distinguish each ultrasonic generator. An RF transmitter module is installed on a mobile robot to invoke one of the ultrasonic generators as desired.

Fig. 1 illustrates the localization procedure for the mobile robot. To initiate the localization process, a mobile robot transmits an RF signal to a beacon at time t_0. When the beacon receives the RF signal corresponding to its own ID, it sends out an ultrasonic signal to a ultrasonic receiver which is mounted on the mobile robot, which reaches the robot at time t_1. Using the known traveling speed of the ultrasonic signal and the traveling time, $t_1 - t_0$, the distance from the beacon to the ultrasonic receiver can be calculated. While the mobile robot is traveling in the room, the distances to other beacons are measured continuously.

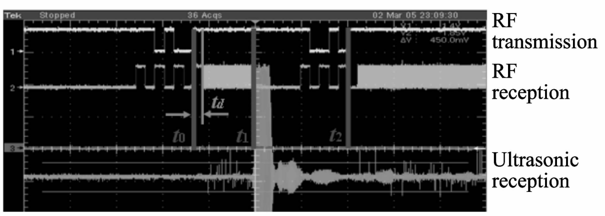

Fig. 1 Ultrasonic sensor and RF transmitter timing

The distance from a beacon to the mobile robot can be defined in terms of mobile robot and sensor parameters as follows

$$s = t_1 - t_0 - t_d, \tag{1}$$

where t_d is the delay time in the beacon.

$$v = 331.3 + 0.606 \times T, \tag{2}$$

where T is the temperature in degrees Celsius which can be received using temperature sensor in the robot. Then the distance, d, between the beacon to the ultrasonic receiver can be calculated as

$$d = v \times s. \tag{3}$$

To simplify and improve the filtering process, out-of-range data are pre-filtered out based on the following heuristics:

1) When $d_1 > d_{\max}$ or $d_1 < d$ min, discard the ID, where $d_{\max}$ and $d_{\min}$ is the possible maximum and minimum distances, respectively, which can be estimated for a given room.

2) When the distance between two consecutive ultrasonic signals is less than $d_{\min}$, discard the later one which can be considered as a reflected one.

In the past indoor absolute-positioning schemes, the position of a mobile robot in a three dimensional space can be calculated basically from the distance information from three beacons which have their own absolute position information. That means that three or more beacons must be deployed in the working range of one beacon, and there is no obstacle blocking the ultrasonic signal between a beacon and the mobile robot. However, in real greenhouse situations, there are many stems, leaves and other obstacles. For irregular mobile space of the rail robot, a large number of beacons need to be deployed by the traditional scheme. Besides, for very time positioning, more than three ultrasonic transmitters are needed to set out ultrasonic waves, increasing noise level. Although, in some schemes, only one ultrasonic transmitter which is mounted on the mobile robot sets out ultrasonic wave, more beacons receive ultrasonic signal[7-9]. These schemes rely on bidirectional communications between the mobile robot and beacons or other equipment. The system complexity increases.

As a main contribution of this paper, an inverted traditional localization scheme is proposed.

In this scheme, two ultrasonic receivers are installed at the same distance from the center of robot. Considering the accuracy and simplifying algorithm, we set the receivers and the ultrasonic transmitters of the beacons at the same horizontal plane.

As shown in Fig. 2, when the beacon receives its own ID, it sends back ultrasonic wave, and then two ultrasonic receivers receive an ultrasonic signal at different time. Using the known traveling speed of the ultrasonic signal and the traveling time, the distance from the beacon to the ultrasonic receivers can be calculated. It is assumed that the coordinates of the ultrasonic receiver No. 1, No. 2 and the beacon are $(-a, 0)$, $(a, 0)$ and (x_{br}, y_{br}), respectively.

Then, geometric relationships of them can be represented as

$$\begin{cases} (x_{br} - (-a))^2 + y_{br}^2 = L_1^2, \\ (x_{br} - a)^2 + y_{br}^2 = L_2^2, \\ x_{br}^2 + y_{br}^2 = L^2. \end{cases} \tag{4}$$

After solving the equation and choosing the solutions which include a positive y_{br}, we can get the relative position of the beacon to mobile robot in coordinate system of robot. Through the coordinate transformation, the position of a mobile robot can be calculated basically from the beacon's absolute position information in the global coordinate system.

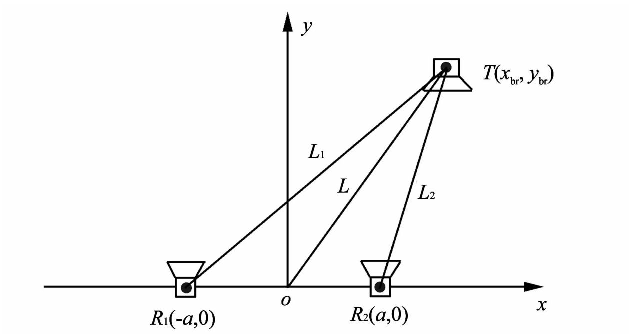

Fig. 2 Geometric relationships of ultrasonic sensors

Transforming from the robot coordinate system to the beacon coordinate system can be described as

$$\begin{bmatrix} X_b \\ Y_b \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X_r \\ Y_r \end{bmatrix} + \begin{bmatrix} X_r \\ Y_r \end{bmatrix}, \quad (5)$$

where (X_b, Y_b) is the coordinate of one point in beacon coordinate system, (X_r, Y_r) is the point coordinate in the robot coordinate system, θ is the angle between the two coordinate systems.

Transforming from the beacon coordinate system to the global coordinate system can be represented as

$$\begin{bmatrix} X_g \\ Y_g \end{bmatrix} = \begin{bmatrix} X_b \\ Y_b \end{bmatrix} + \begin{bmatrix} X_{bg} \\ Y_{bg} \end{bmatrix}, \quad (6)$$

where (X_g, Y_g) is the coordinate of one point in global coordinate system, (X_{bg}, Y_{bg}) is the beacon coordinate in the global coordinate system.

As stated above, the inverted traditional localization scheme can provide the position, localization using only one beacon.

When the robot is operating on the circular-arc rail, a dynamic localization scheme is proposed. In Fig. 3, the initial location of the mobile robot is represented as $P = [x_n, y_n]^t$, and command velocity of the mobile robot, v_n, is defined as $V_n = [\dot{X}_n, \dot{Y}_n]^t$. As shown in Fig. 3, the v can be represented as Eq. (7)

$$\begin{bmatrix} \dot{X}_n \\ \dot{Y}_n \end{bmatrix} = \begin{bmatrix} v_n \cos\alpha_n \\ v_n \sin\alpha_n \end{bmatrix}. \quad (7)$$

It is assumed that the distance from the mobile robot to the beacon, d_n, is known, and the distance information from a beacon, d_{n+1}, is measured by the mobile robot. Therefore, the position of the mobile robot can be represented as

$$\begin{bmatrix} X_n \\ Y_n \end{bmatrix} = \begin{bmatrix} -d_n \cos\varphi_n \\ d_n \sin\varphi_n \end{bmatrix}. \quad (8)$$

Differentiating both sides w. r. t time, the velocity can be represented as

$$\begin{bmatrix} \dot{X}_n \\ \dot{Y}_n \end{bmatrix} = \begin{bmatrix} -\cos\varphi_n & d_n \sin\varphi_n \\ \sin\varphi_n & d_n \cos\varphi_n \end{bmatrix} \begin{bmatrix} \dot{d} \\ \dot{\varphi} \end{bmatrix}. \quad (9)$$

This equation can be transformed into a discrete system equation by replacing $\dot{d}$ as Δd/T and $\dot{\varphi}$ as $\Delta\varphi/T$

$$\begin{bmatrix} \Delta d \\ \Delta\varphi \end{bmatrix} = T \begin{bmatrix} -\cos\varphi_n & \sin\varphi_n \\ \frac{1}{d_n}\sin\varphi_n & \frac{1}{d_n}\cos\varphi_n \end{bmatrix} \begin{bmatrix} \dot{X}_n \\ \dot{Y}_n \end{bmatrix}, \quad (10)$$

where $\Delta d = d_{n+1} - d_n$ can be obtained by the distance measurement to the beacon, and T represents the sampling period for the distance measurement.

In Fig. 3, the O' is the centre of the circular-arc rail, R is the radius of circular-arc rail, C is the distance from the beacon to O', α_n can be derived from Fig. 3.

$$\alpha_n = \frac{\pi}{2} - \varphi_n - \beta_n. \quad (11)$$

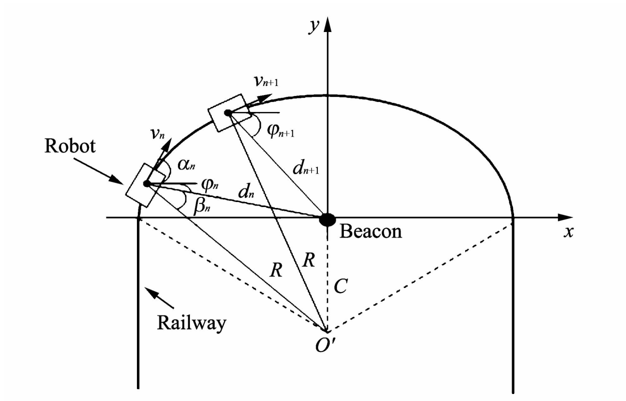

Fig. 3 Circular-arc rail localization algorithm

According to the Law of Cosines

$$\cos\beta_n = \frac{R^2 + d_n^2 - c^2}{2Rd_n}, \quad (12)$$

$$\cos\left(\beta_n + \frac{\pi}{2}\right) = \frac{C^2 + d_n^2 - R^2}{2Cd_n}. \quad (13)$$

Plugging the known R, C and d_n into Eq. (12) and Eq. (13), β_n and φ_n can be obtained. And plugging β_n, φ_n and d_n into Eq. (11), Eq. (8), Eq. (10), $\Delta\theta$ can be obtained. Therefore, the new location can be estimated as

$$\begin{bmatrix} d_{n+1} \\ \varphi_{n+1} \end{bmatrix} = \begin{bmatrix} d_n + \Delta d \\ + \Delta\varphi \end{bmatrix}. \quad (14)$$

Using Eq. (8), the next location coordinates, x_{n+1} and y_{n+1} are obtained.

3 Attenuation compensation

As a mechanical wave, the amplitude and intensity of ultrasonic wave are attenuated exponentially when transmitted through a medium with increasing distance. If amplitude of the ultrasonic signal is smaller than a certain value (ultrasonic detection voltage), the ultrasonic receiver cannot sense the ultrasonic signal. In this study, an attenuation compensation module that utilizes an alterable ultrasonic detection voltage was used to decrease the error. The ultrasonic detection voltage can be obtained using the following equation:

$$V = V_0 - A_0 e^{-ax}, \quad (15)$$

where A_0 is the amplitude of the propagating wave at some location, V_0 is the ultrasonic detection voltage that was used in this location, a is a positive attenuation coefficient, the amplitude is the reduced amplitude when the wave has traveled a distance x from the initial location, and the quantity a is the attenuation coefficient of the wave that is traveling in the x direction[10].

4 Experiments

The localizer that was attached to the robot to set the RF and receive ultrasonic signals and to measure the distance from the beacons was designed using DSP TMS320C2406, and the ultrasonic transmitters were designed using MSP430.

The deployment of the beacons and the route of the rail robot in greenhouse are shown in Fig. 4. Based on the range of ultrasonic wave and the distribution of obstacles in greenhouse, ten beacons were deployed on the walls or beams of the greenhouse.

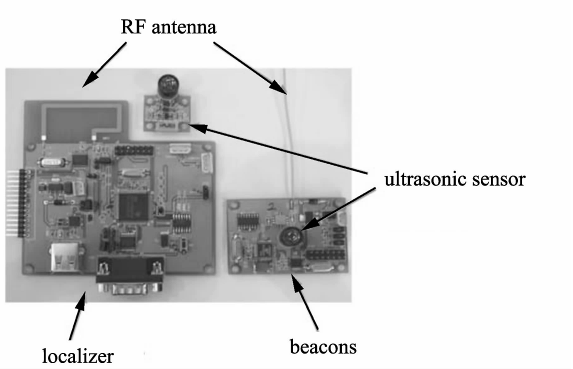

Fig. 4 Picture of the beacon and the localizer

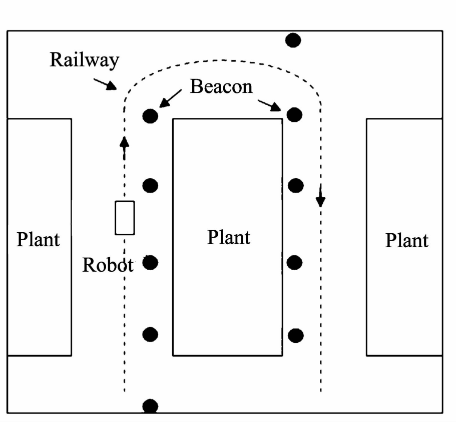

Fig. 5 The deployment of the beacons

There are two different experiments to prove the effect of attenuation compensation and function of inverted traditional localization navigation system. The first experiment, a beacon is used to prove the function of attenuation compensation. In this experiment, at a certain distance, a position is measured and compared with true actual value. The results are shown in Fig. 6. In Fig. 6(a), the error increased as the distance became longer without attenuation compensation. On the other hand, as shown in Fig. 6(b), with attenuation compensation, the error basically maintain at the same level.

In the second experiment, all beacons are used to prove the function of inverted ABS localization system in the practical application. Considering the robot just working on straight rail, so only the positions of robot in straight railway are measured. The result is shown in Fig. 7. Besides the bigger errors which exist at the junction of the range of adjacent beacons, no serious faulty results occurred. The localization method of a rail robot in greenhouse presented in this paper is feasible and effective.

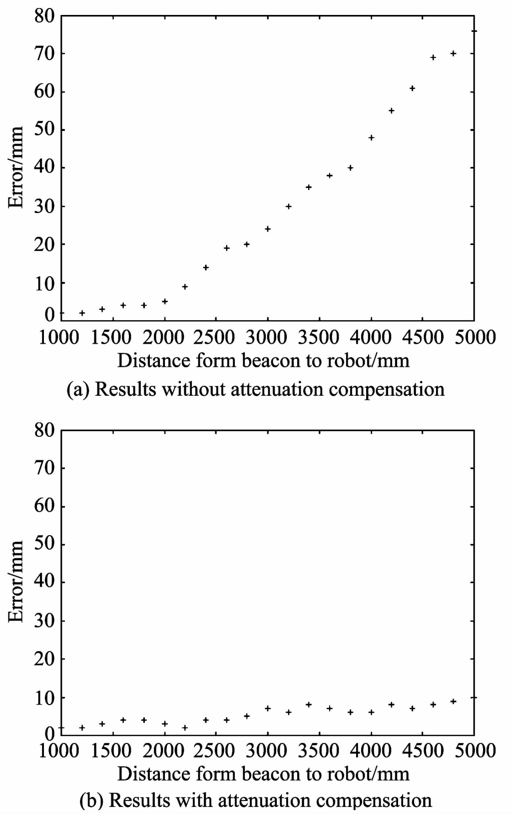

Fig. 6 The function of attenuation compensation

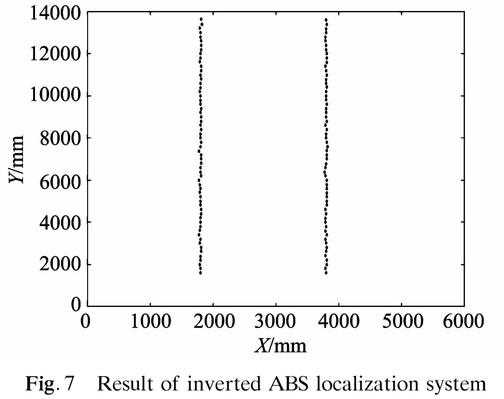

Fig. 7 Result of inverted ABS localization system

5 Conclusions

In this paper, we have presented an inverted ABS localization system for navigation of a rail Robot for working in greenhouse. The position of a beacon in coordinate system of robot can be calculated basically from the distance information from the beacons to two ultra-sonic receivers which are mounted on the robot. Based on the coordinate transformation, the position of a mobile robot can be calculated basically from the beacon's absolute position information in the global coordinate system. Through inverted ABS localization system, the rail robot can receive its position information in its entire working space, at the same time, the number of requisite beacons is reduced, which can save much money.

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