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単一受信機のみを用いた超音波3次元トラッキングシステム
Ultrasonic-based 3D Tracking System using a Single Beacon

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In this study, we present an ultrasonic-based three dimensional tracking system which can track the position of the object with high accuracy using only a single beacon. Our proposed system uses the time of flight of ultrasonic wave to calculate the distance between the transmitter and the receiver. We applied the Phase Accordance Method which can accurately detect the arrival time of the ultrasonic signal and increase the accuracy of distance measurement. The main advantage of our proposed system is that we can precisely locate the position of the moving object in three dimensions by using only one base station. In this paper, we discuss the concept, implementation, experiment, advantages and disadvantages of the proposed system, comparing it to other well-known systems. The experimental results show that our system can measure the position to within accuracy of just a few centimeters.

1. Introduction

In the past decade, the concept of location-aware computing has gained a lot of attention from the researchers in academia and industry all over the world. An important technology that drives the possibility of location-aware computing is the positioning system. While GPS provides very good outdoor location information, its accuracy degrades in indoor environment because the building and wall blocks GPS signal. For this reason, so far there have been attempts to create an indoor location system by a lot of research groups using various approaches. Active Bat[1] and Cricket[2] are some of the important researches in this field. Both systems use different approaches and serve different kind of application. While Active Bat uses active architecture to centralize the system to a single server allowing central monitoring system, Cricket takes on the opposite approach which focuses on decentralization to promote privacy of the user and scalability of the system.

More recent work, Dolphin [3], proposed an innovative approach to improve the performance of ultrasonic localization system by using broadband ultrasonic communication. This improves noise robustness, increases update rate of the system and also allows simultaneous multiple access signaling which addresses dynamic tracking problem in Cricket's user-oriented system.

The disadvantage that most of the existing systems has in common is that they require at least three beacons placing separated at some distance[1, 2, 3]. This creates a beacon placement issue. The beacons have to be placed close together enough so that they are all in the range of the transmitted ultrasonic signal but far separated enough to allow good trilateration. They also need a lot of devices to cover the desired tracking area which increases the cost.

In this paper, we propose an ultrasonic-based object tracking system which can provide accurate coordinate of the tracking object in 3D. Requiring only one pair of transmitter and beacon station, our system has the advantage of easy and low cost of deployment, while still providing accurate position information. Applications which require accurate position coordinate in 3D such as virtual reality games, automated robot control and other pose-aware applications will benefit from our system.

2. System Implementation

In this section, we discuss about techniques for measuring the distance using Phase Accordance Method, the importance of beacon geometry and the overview of the system.

2.1 Distance Measurement using Time of Arrival (TOA) and the Phase Accordance Method

In this research, we use the time difference of arrival of radio and ultrasonic signal by transmitting radio and ultrasonic signal at the same time, and then radio signal will arrive at receiver first because it travels at much faster speed, following by the ultrasonic signal. Since radio propagation time is extremely fast, its propagation delay can be ignored. The time difference of arrival of radio and ultrasonic signal is then converted into distance.

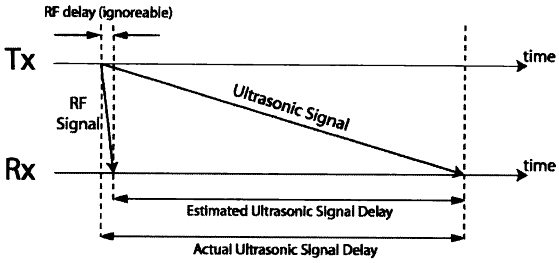


Figure 1: Time difference of arrival between RF and ultrasonic signal

To achieve accurate distance measurement, we need to accurately detect the arrival time of ultrasonic signal. We have adopted the Phase Accordance Method (PAM) [4]. In PAM, a special burst pulse which consists of the transmission of two or more frequencies is transmitted. This special burst pulse creates a unique wave form which is called the Sync Pattern and it can be described as:

$$\sin\, 2\pi f_1 t + \sin\, 2\pi f_2 t = \sin\, \omega_1 t + \sin\, \omega_2 t$$

Then at the receiver, the point where the two carrier phases of the transmitted signal accorded is used to indicate the arrival of the signal as described in [4]. This point is called "Epoch".

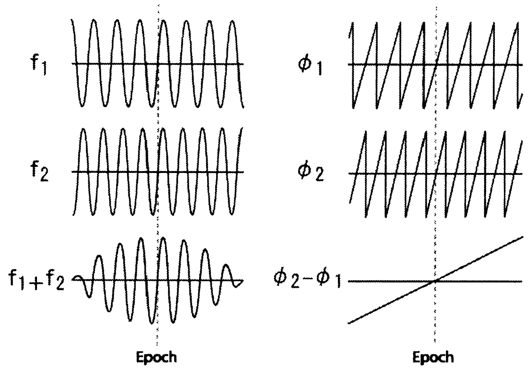


Figure 2: Sync Pattern and its Epoch

From the experiment result in [4], it shows that Phase Accordance Method is capable of providing distance measurements within an error range of less than 1 mm under experimental conditions.

2.2 Finding the Position in 3D

In the proposed system, position of the object in three dimensions can be obtained by using 3 ultrasonic sensors at the receiver using a technique called "3D multilateration," which is the process of figuring out where several spheres intersect. The radius of the each sphere is represented by the distance measured from the transmitter to the receiver. Ideally, the spheres would intersect exactly at one point which is the location of the tracking object. However, in reality there are some errors in distance measurement. We can estimate the true location using least squares method.

With the help of TOA and Phase Accordance Method, we can obtain precise distances from the transmitter to each sensor at the receiver (D1, D2, D3) as shown in Figure 1. Receiver is fixed at known position. We can calculate the coordinate of the transmitter as follow:

$$(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 = r_i^2$$

where (x_0, y_0, z_0) is the coordinate of the object, (x_i, y_i, z_i) is the coordinate of i^{th} sensor, r_i is the distance from transmitter to the i^{th} sensor. Next, we do linearization by subtracting the last equation (k) to get rid of the quadratic terms

$$2x_0(x_k - x_i) + 2y_0(y_k - y_i) + 2z_0(z_k - z_i) = r_i^2 - r_k^2 - x_i^2 - y_i^2 - z_i^2 + x_k^2 + y_k^2 + z_k^2$$

So now we get Ax = B,

$$\begin{bmatrix} 2(x_k - x_1) & 2(y_k - y_1) & 2(z_k - z_1) \\ 2(x_k - x_2) & 2(y_k - y_2) & 2(z_k - z_2) \\ \vdots & \vdots & \vdots \\ 2(x_k - x_{k-1}) & 2(y_k - y_{k-1}) & 2(z_k - z_{k-1}) \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = \begin{bmatrix} r_2^2 - r_k^2 - x_1^2 - y_1^2 - z_1^2 + x_k^2 + y_k^2 + z_k^2 \\ r_2^2 - r_k^2 - x_2^2 - y_2^2 - z_2^2 + x_k^2 + y_k^2 + z_k^2 \\ \vdots \\ r_i^2 - r_k^2 - x_i^2 - y_i^2 - z_i^2 + x_k^2 + y_k^2 + z_k^2 \end{bmatrix}$$

We can solve the coordinate of the object by,

$$x = A^+ B$$

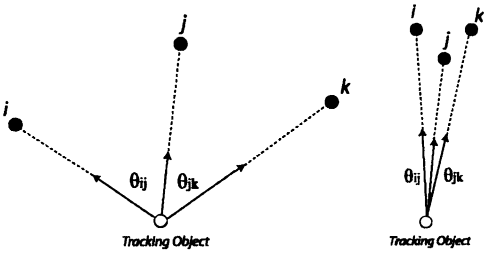
where A^+ is a Moore-Penrose Inverse of Matrix A

2.3 Beacon Geometry

Beacon placement strongly affects the quality of localization. To achieve good tracking accuracy, traditional systems such as Cricket and Active Bat rely on good beacon geometry which means that beacons have to be deployed far apart from each other at some distance to create a good wide angle between the tracking object to the beacons as shown in Figure 4.

Figure 3: On the left is an example of close alignment of beacons. On the right is a wide alignment of beacons.

However, this makes the deployment of the system more difficult and costly. A lot of beacons have to be deployed to cover a tracking area.



(a) (b)

Figure 4: The larger the angle θ, the wider we have to separate the sensors

In this research, we integrated three ultrasonic sensors onto a single beacon. This, of course, is bad beacon geometry but on the other hand, we gain the ease and cost of deployment. Thanks to Phase Accordance Method which provides extremely accurate distance measurement, we are able to maintain the level of accuracy which compatibles with traditional method while using only one pair of transmitter and receiver beacon. Cricket and Active Bat were not able to do this because they did not apply special technique to improve distance measurement accuracy.

2.4 System Components

In this section, we give an overview on our current system. The hardware we use in the experiment is shown in Figure 5.

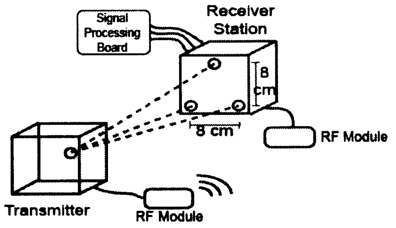


Figure 5: Overview of current system

Using Phase Accordance Method, we can obtain very accurate distance measurement. It is accurate enough to allow the integration of three ultrasonic sensors in one beacon unit, while still produce high performance tracking system. We mounted three ultrasonic microphones onto a single beacon of size 8 x 8 x 8 cm. By using three distance measurements from a transmitter to these sensors, we can calculate the location of the transmitter. The receiver is connected to the processing board which is used to calculate the epoch in Phase Accordance Method. Both receiver and transmitter are each connected to an RF module which is used for time synchronization and other data communication.

3. Experiment and Result

In order to investigate the performance of our system, we have conducted experiments for both static case and dynamic case. We created a mobile robot tracking system. In this system, mobile robot attached with ultrasonic transmitter is moving freely inside the tracking area. Ultrasonic receiver beacon attached on the ceiling is used to receive ultrasonic signal from the moving robot and then calculate the location of the robot. In order to compare the performance of our tracking system with the ground truth, we use vision-based tracking method which has very high accuracy as a reference. We discuss about the experiment setting, procedures, and results in this session.

3.1 Experiment Setting

The experiment setting is shown in Figure 6. The tracking area is 1.8 m x 1.8 m, surrounded by small fence. A 3-channel ultrasonic beacon is mounted on the ceiling at the height of 2.5 meters. A camera which is used for vision-based tracking is mounted next to the ultrasonic beacon on the ceiling. For moving object, we use a commercial mobile robot called iRobot as a tracking object. An ultrasonic transmitter is mounted onto the robot. Ultrasonic receiver beacon, transmitter and server are each attached with an RF module which is used for data communication purpose.

The transmitter at robot transmits an ultrasonic sync pattern signal to the receiver beacon on the ceiling. Receiver beacon receives the signal and calculate the location of the robot. The location information of the robot is then forwarded to the server for visualization and data collection for further analysis.

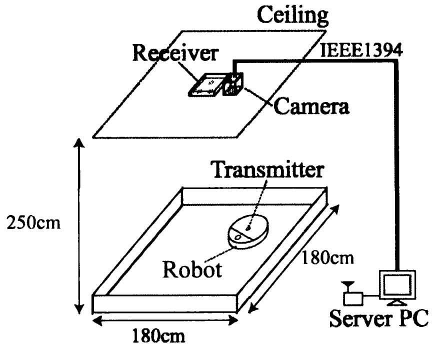


Figure 6: Experiment Setting

The reason we limited the tracking area to 1.8 m x 1.8 m is because the limitation of the signal reception angle of the ultrasonic sensor. The off-the-self ultrasonic sensor used in this experiment has a beam angle of approximately 60 degrees. As can be seen from the Figure 7, signals coming in from wider angle are degraded and should not be used.

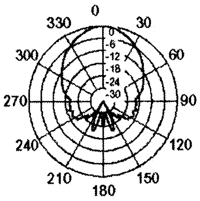


Figure 7: Beam angle of ultrasonic sensor used in the experiment

3.2 Evaluation Method

Evaluation of the accuracy of dynamic object tracking is one of the tricky issues. For this experiment, we use a vision-based localization which has very high accuracy as a ground truth measurement. By comparing the result from our tracking system with the result from vision-based tracking, the performance of our system can be assessed. In the vision-based localization, a camera connected to the PC captures an image of the infrared LED mounted on the robot. The captured image is then processed by the PC to determine the actual coordinates of the robot from the position of the LED in the image. In order to make the calculation simpler, the camera has an IR filter in front of its lens so that it can capture only the IR LED of the robot.

The time synchronization between the vision and the ultrasonic localization is made by using the trigger packets. When the RF module on the server receives the trigger packets, it orders the PC to immediately capture a frame from the camera. This synchronization guarantees that the results of the two localizations refer to the robot at the same instant.

We assess the accuracy of the system by the average Euclidean distance error between the estimated coordinate of the mobile device and the receiver's coordinate. So,

$$Error=\sqrt{(x_m-x_0)^2+(y_m-y_0)^2+(z_m-z_0)^2}$$

where (x_0, y_0, z_0) is reference coordinate and (x_m, y_m, z_m) is measured coordinate of the object.

3.3 Experiment: Static Case

For static case, we place the robot at the center and each corner of the tracking area as shown in Figure 8. We measure the real position physically using measurement tape. The robot is set to non-moving mode. We take the location samples for 2000 times for each position.

First, we place the robot at the center point (P0). Then, we calibrate the system and take sample data. Next, we change the position of the robot and take sample data again, starting from point P1 to P4. The result from the experiment is shown in table 1 below.

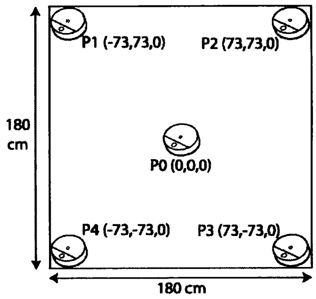


Figure 8: Static Robot Tracking Experiment

It can be seen that the result taken at P0 shows better accuracy than other points. The reason is because, at the corners of the tracking area, the angle from the transmitter to the receiver is wider and the distance between them is longer as well. From Figure 7, it shows that the signal degrades if the angle is wider. Also, this agrees with the result from the experiment in original paper [1].

Table 1: Experiment data collected from Static Case

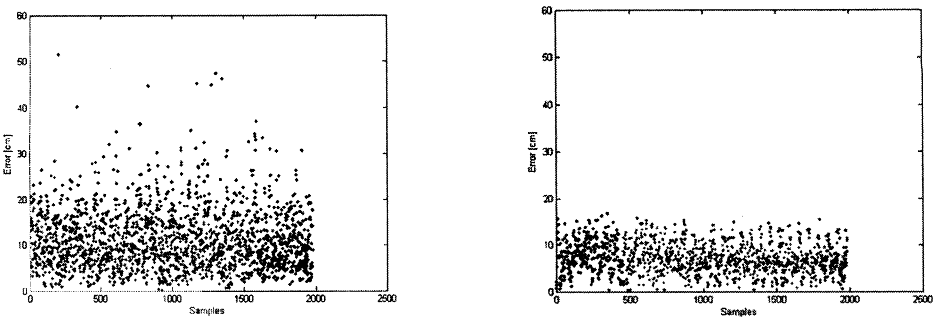
Point	Real Position	Average Tracking Result	Position Error SD
P0	(0,0,0)	(0.308 , 0.276 , 0.023)	0.353 cm
P1	(-73 , 73 , 0)	(-73.774 ,75.100, -0.362)	0.821 cm
P2	(73 , 73 , 0)	(74.350 ,74.638,-0.254)	0.925 cm
P3	(73 ,-73 , 0)	(74.804 ,73.212,-0.148)	0.849 cm
P4	(-73 ,-73, 0)	(-75.253 ,73.638,-0.332)	0.766 cm

However, from experiment result, the accuracy of the system is considered very satisfying for non-moving object tracking scenario. It is safe to conclude that our system can locate the position of the non-moving object with the average error of less than 1 cm in three dimensions in experimental environment.

3.4 Experiment: Dynamic Case

In this experiment, we track the robot when it is moving. The experiment setting is the same as static case except that instead of placing robot at fixed location, we let the robot run freely in the tracking area. We let the robot run and then take the location samples for about 30 minutes.

Furthermore, we did this experiment with and without averaging filter and compare them together. Averaging Filter (AVF) smoothes tracking data, reducing the effect of noise. It can be done by taking 10 distance samples for



(a) Without Averaging Filter

(b) With Averaging Filter

Figure 8: Position error graphs from dynamic tracking experiments

each sensor in 1 second (10 Hz) and then simply calculate the average, to give a better estimate of its true value, where n is number of samples and x is the measured distance.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The result graphs from dynamic tracking experiment without and without averaging filter are shown in Figure 8. We summarized the important values in table 2. From table 2, it can be seen that averaging filter can significantly help increasing the performance of our tracking system. Reducing the average position error by 48.37 percent, the standard deviation of position error by 52.98 percent and maximum position error by 65.7 percent, averaging filter has proved to be useful for our tracking system.

Table 2: Comparison of the cases with and without averaging filter

Experiment	Average Position Error	Position Error SD	Max Pos Error
Without AVF	10.222 cm	6.584 cm	51.565 cm
With AVF	5.277 cm	3.096 cm	17.688 cm

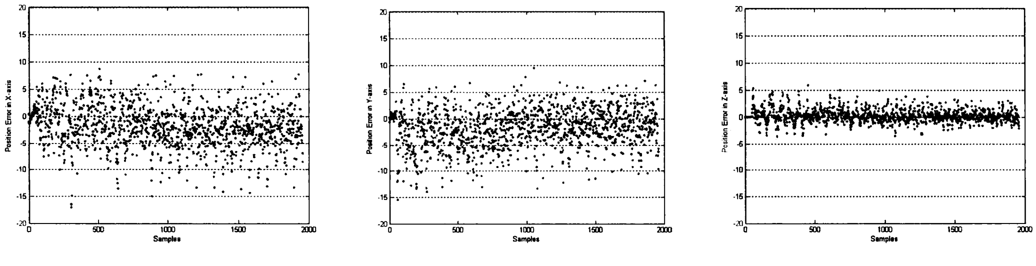
Further analysis of the result can be seen in table 3 where the standard deviations of position errors in each axis are shown. We can clearly see that X and Y axis have higher standard deviation than Z-axis. Figure 3 in session 2.3 helps better understanding why the result looks like this. It illustrates the situation similar to what happened in our experiment, using similar sensor geometry.

Table 3: Comparison of position error SD in each axis

Axis	X-axis	Y-axis	Z-axis
SD of Position Error	3.897 cm	3.668 cm	1.273 cm

The sensors alignment in X and Y axis represent the error in horizontal plane while Z axis represents vertical plane. It can be seen from Figure 9 that, with only a small distance measurement error, the result position in XY plane can vary a lot while the Z plane does not vary much. This agrees with the theory of beacon geometry discussed.

However, despite close alignment of ultrasonic sensors at the receiver (thus, the benefit of single beacon), our system has relatively high accuracy with the average



(a) X-axis

(b) Y-axis

(c) Z-axis

Figure 9: Position Error in each axis

position error of 5.277 cm and maximum error of less than 20 cm which is considered to be useful for many applications such as automated robot navigation.

One of the sources of error that might affect the result of the experiment is the temperature variation during the experiment period. Speed of ultrasound varies when temperature changes. Another possible error is the latency between camera-based tracking system which is used as a reference and the ultrasonic-based tracking system. This latency reduces the reliability of the camera-based tracking system as a ground truth.

4. Conclusion and Future Work

In this paper, we have presented our development of an ultrasonic-based 3D tracking system using a single beacon. We have shown that we can achieve the high accuracy physical coordinate of the tracking object in three dimensions using only one pair of transmitter and receiver beacon. We achieved an average accuracy of about 5 cm. With this feature, creating a low-cost and easy-to-deploy indoor tracking system is possible.

Our future plan is to apply different filtering method. Even though averaging filter is proved to be capable of reducing the effect of noise in tracking data. It produces a small delay in reporting location information since it has to wait for a number of samplings to be done before calculating the average. For fast moving object, this slight delay can cause large error in real-time application.

Furthermore, even though we achieved satisfying result in this experiment, however, the robot that is used as a tracking object is moving at slow speed. When the object is moving at faster speed, the Doppler Effect will take into account. Therefore, we plan to add Doppler Effect compensation to achieve accurate fast-moving object tracking system.

Some other position estimation techniques will be applied and experimented for the best result. We also plan to deploy more beacons inside the building to cover wider tracking area. To achieve that, we have to develop a protocol to handle the communication of the ad-hoc wireless sensor network.

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