An Implementation and Evaluation of Indoor Ultrasonic Tracking System

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Researches on context-aware computing have shown that monitoring of the objects locations can determine the state of an environment. By tracking the objects locations, it is possible to derive their orientations and motions in beside of their locations. Many researches on the ultrasonic-based location-aware systems in an indoor environment are based on particular scenarios. We introduce an ultrasonic locating system used in the home and office environment. We propose a multilateration positioning system by using a direct substitution method. We have investigated our tracking system accuracy and performance in such environments. The experiment tests results show that our tracking system is performing well and we conclude the future work of our tracking system in the last part of this paper.

超音波型屋内測位システムの実装と評価

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屋内環境において様々な適応型サービスを実現する際に，オブジェクトの位置情報が重要となる．屋内において位置情報を取得する手段としては Active Bat システムのような超音波型の測位システムが有用である．しかしながら Active Bat システムはそれを利用したアプリケーションに主眼が置かれており，システム自体の性能評価，特に実環境における動的な評価については言及されていない．このような観点から，本稿では超音波型屋内測位システムを実装し，その評価を行う．また，本稿ではターゲットの位置を高速に求めるためのアルゴリズムについても言及する．

1. Introduction

Indoor environments, such as homes and offices are rich in computing and communications resources. It is very likely that the density of devices in these surroundings will increase in the future, as the improvement in digital technologies make computers smaller, cheaper and lower powered, and networks, both wired and wireless, become more commonplace. By integrating these devices in our surrounding, many kinds of services and applications can be accomplished[1]. Thus, ubiquitous computing environment becomes more feasible.

Context-aware application can be considered as the main application in ubiquitous environment. In the context-aware systems, the dynamics model of environment, where the devices and applications react according to the changes of their surrounding, can be achieved. Many different quantities of objects (e.g. motion, weight, temperature) can be monitored by computer in order to build up this model. However, normally each quantity is measured by a different sensor system. As the numbers and diversities of sensors in an environment increase, the physical infrastructure required to support them (e.g. wiring and interfaces) becomes more complex, and the problems of managing and collating different types of sensor information arise. It seems more desirable, therefore, to investigate whether information gathered using a single type of sensors is sufficient to let the devices and applications efficiently react towards changes in the operation of context-aware systems.

Researches on context-aware computing have shown that monitoring of the objects locations is a feasible method for determining the state of an environment. By accurately tracking the objects

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locations, it is also possible to derive other useful information, such as their orientations and motions. Location-aware computing system is the system whose behavior can be determined by these types of data. Location-aware computing systems embody a practical subset of the context-aware computing paradigm, and several systems based on this principle such as Active Bat, Active Badge and Cricket location system that have already been developed.

From the view of service area and functionality, GPS is the most suitable candidate system for providing location information in outdoor environment. Meanwhile, from the view of precision and versatility, ultrasound-based location information system can be considered the most suitable candidate system in the indoor environment.

Present researches on ultrasound-based location information systems show the noticeable performance in particular scenarios. But the precision and reliability have not been shown in office or home environment.

To evaluate the precision and performance of ultrasonic locating system in more practical environment such as office and home environments, we implemented an ultrasonic locating system in such environments and the performance and precision of the system were also evaluated. An easier location-estimating algorithm is also used in our tracking system. By using this algorithm, location-estimating program can be developed very easily and the performance becomes adjustable when applied into location-aware applications.

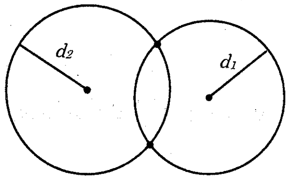
2. Indoor Ultrasonic Tracking System

2.1 Principle of positioning

To determine the location of object, the concept of trilateration is used in the tracking system. Object-receiver distance can be obtained by using times-of-flight of ultrasound. Then object location can be estimated by using object-receiver distances obtained from three or more receivers.

Distance Calculation

Distances between object and receivers can be determined by using the transmission time of ultrasound. Assume the transmission time of ultrasound between object and a receiver is T_d, the speed of ultrasound is V_s, and the distance between object and receiver is D, then D can be calculated by using following relationship:



Measurement of distances d_1 and d_2 to the transmitter from two receivers allows us to find out the two intersect point of these two circles

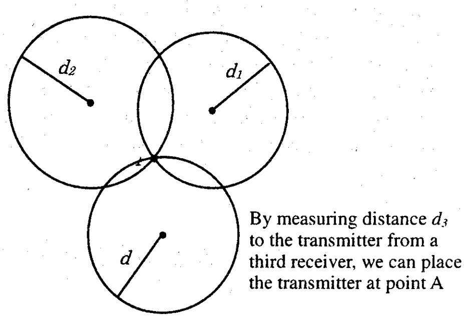


Fig. 1 Position estimated by multilateraltion

$$D = T_d \times V_s \tag{2.1}$$

Since V_s is known, if T_d can be obtained, distance can be calculated easily.

The speed of sound in air is affected by a number of environmental variables, such as the air temperature, relative humidity, air composition, and so on. Among these, changes in temperature have by far the greatest effect; raising the air temperature from 10℃ to 30℃ increases the speed of sound by over 3%, while a change in relative humidity (the next most significant variable) from 0% to 100% increases the speed of sound in air at 20℃ by only 0.3% [4]. It is clear, therefore, that a good estimate of the speed of sound can be determined by measuring the air temperature alone. Assume the air temperature within the room is uniformly, a measurement of air temperature at a single point can be used to estimate V_s, via the following relationship:

$$V_s = 331.45 \times \sqrt{\ } (1 + T / 273.15) \text{ m/s} \tag{2.2}$$

Where T is the air temperature in degree Celsius.

Positioning by Multilateration

The principle of multilateration is demonstrated in Figure 1; a transmitter known to be at distance x from a receiver must be located on a sphere of radius x centered on that receiver. Four such spheres around receivers placed in three-dimension space, such that they are not coplanar and no three are collinear, will intersect at only one point. The transmitter must have been located at this point in order to generate the observed distances.

Consider a set of receivers placed at points on a horizontal ceiling. Suppose that a stationary world reference frame is defined, with orthogonal coordinate axes **x**, **y** and **z**, such that all points with constant **z** coordinate are horizontal, and assign the **z**-coordinate 0 to the horizontal plane where the receivers lie. Then suppose that a Mobile Device (MD) is at the coordinate (u,v,w), where w<0 (indicating that the MD is below the ceiling), and that its distance from a receiver at the coordinate (x,y,0) is l. It can be shown that

$$l = \sqrt{((x^2+y^2)+(u^2-2xu)+(v^2-2yv)+w^2)} \quad (2.3)$$

Equation 2.3 describes an ideal relationship situation where all distances and positions are measured with perfect accuracy. Suppose, however, that this relationship is viewed in a setting where an estimate of the MD's position is to be determined, based on a set of distances $l_1,\ldots,l_n$ simultaneously measured from it to a corresponding set of non-collinear receivers at position $(x_1,y_1,0),\ldots,(x_n,y_n,0)$, where $n \geqq 3$. The distance measurements and surveyed positions of the receivers will be subjected to experimental error, and so Equation 2.3 must be corrected, as below, by introducing an additional term ε that can account for these errors:

$$l_i = \sqrt{((x^2+y^2)+(u^2-2xu)+(v^2-2yv)+w^2)} + \varepsilon_i \quad (i = 1,\ldots,n) \quad (2.4)$$

This equation can be regarded as a nonlinear model [5]. The process of nonlinear regression can be used to fit the collected values of l, x and y to the model of the parameters u, v and w.

Estimation for the position of object can then be determined as the coordinate (u, v, -|w|), taking the negative root of w^2 to resolve the position ambiguity because the mobile device is below the ceiling.

2.2 Principle of system design

To implement an ultrasonic tracking system, the following entities are indispensable:

(1) Ultrasound transmitters
(2) Ultrasound receivers
(3) PCs for distance calculation and location estimation

Ultrasound transmitters are used to transmit ultrasound pulses that can be used to calculate the object-receiver distance. Ultrasound receivers are used to detect the ultrasound pulses that are transmitted by ultrasound transmitters. Any ultrasound transmitter-receiver pair can be used to obtain the transmission time (times-of-flight) of ultrasound pulses between transmitter and receiver.

After obtaining the times-of-flight of ultrasound pulses, the distance between transmitter and receiver can be calculated by using the transmission characteristic of ultrasound.

Some special measures are also taken when implement an ultrasonic tracking system in indoor environment:

(1) Ultrasound signal can be easily blocked by object. To lower the probability that the transmitted ultrasound pulses being blocked, a wide-angle ultrasound transmitter is needed or some transmitters are needed to form a transmitter matrix.

(2) To determine the location of object, three or more receivers are needed. Since objects are free to move around, to guarantee there are more than three receivers detect the ultrasound pulses from transmitter, ultrasound receivers must be placed on the ceiling and spread out in the indoor area.

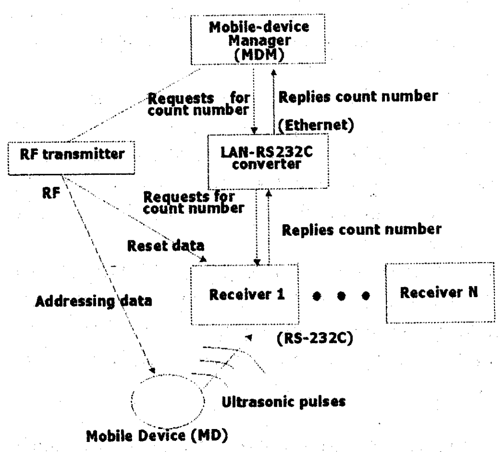


Fig.2 Overview of ultrasonic tracking system

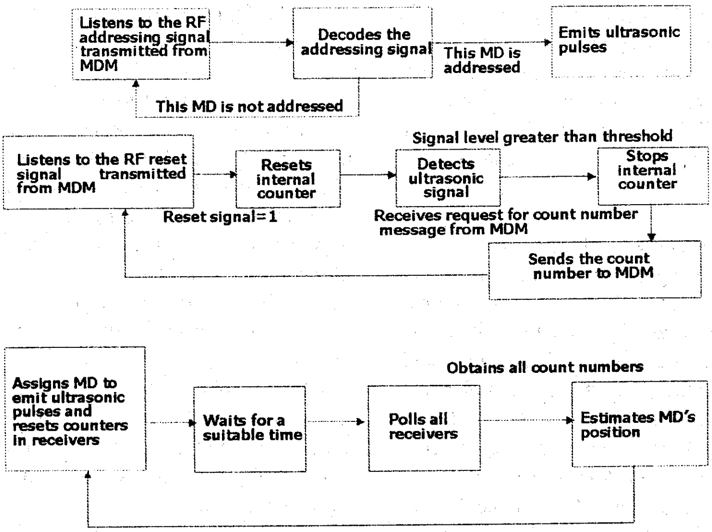


Fig. 3 Operating state diagrams of MD, receiver and MDM

(3) To obtain the times-of-flight of ultrasound, there must be a communication interface between receivers and PCs. Thus, PCs can obtain times-of-flight of ultrasound and then using the information to calculate distances and estimate location of objects.

2.3 System Architecture

The indoor ultrasonic tracking system has following main entities:

(1) One or more MDs are attached to the objects to be tracked. MDs are wireless, and have a unique ID, a RF receiver, and an ultrasound transducer that is capable of emitting ultrasonic pulses.
(2) A set of receivers, which placed at known points on the ceiling of the room where objects are to be tracked. Receivers detect the ultrasonic pulses emitted from the MDs, and measure the time-of-flight of those pulses using on board counters.
(3) A computing device called Mobile Device Manager, or MDM, which transmits RF addressing signal containing an ID. Then MDM gathers ultrasonic pulse time-of-flight from the receivers.

Figure 2 shows the overview of the ultrasonic tracking system. The times-of-flight of ultrasound pulses are determined by measuring their arrival times at receivers relative to their times of emission from MDs. Some degrees of synchronization between MDs and receivers are therefore required in the tracking system. In the proposed system, MD-receiver synchronization is provided by the MDM addressing messages, which are detected and decoded by all MDs and receivers. The addressing message consists of 8-bit data. The first 7-bit data stands for MD ID and the last bit of the message stands for the reset bit. MDs only respond to the first 7-bit ID data while receivers only respond to the last bit.

If a MD receives an addressing message containing its unique ID, it immediately transmits ultrasonic pulses. Since the MDM addressing messages travel at the speed of light, the times-of-flight of those messages will be small, and will certainly be insignificant compared to the ultrasonic transit time that is to be measured.

If a receiver receives an addressing message, the receiver decodes the message and only care about the LSB of the message. Logic high of the LSB of addressing message indicates the reset signal to receiver. Thus, receivers' counters can be reset and synchronized with MDs' action.

The ultrasonic tracking system uses ultrasonic receivers to detect the ultrasonic pulses, looking at the pulse envelope to determine its time of arrival. When an ultrasonic receiver detects an ultrasonic pulse, the pulse will be amplified, rectified, and smoothed, then the resulting pulse envelope will be compared with the threshold. If the envelope is larger than the threshold, a pulse is sent to FPGA and makes the counter in FPGA stop. After stopping the counter, only if the reset signal comes to receiver again, FPGA will no longer accept any stopping pulses generated by comparator.

Finally, MDM polls all receivers for obtaining counting numbers. Then MDM uses these counting numbers to determine MD's position. The operating state diagrams of MD, receiver, and MDM are shown in Figure 3.

3. Positioning algorithm

A positioning algorithm called Direct Substitution Method is used in our tracking system. It is developed by using the moving characteristics of human beings and objects.

3.1 Concept of the positioning algorithm

Although multilateration method can be used to determine MD's position, some problems have to be improved or avoided:

(1) In multilateration method, to estimate the 3D position of MD at least four receivers have to detect the ultrasonic pulses emitted from MD or the answer of the mathematical equation in nonlinear regression may become divergent, the position cannot be found if the answer becomes divergent.

(2) There are errors from distance measurements, if one of the MD-receiver distances has too large error, the answer will become divergent in multilateration method.

(3) Selection of reference receivers does affect the estimate result.

The assumption of Direct Substitution Method is that objects in indoor move with relative slower speed than in outdoor environment. So the actual position of the object must be located within a limited area whose center is the last position of the object. Thus, we can find the actual position of the object in this area rather than searching the whole area. Since the MD-receiver distances are given, by substituting all points in the limited area into distance equations, the position with smallest error can be found out. Figure 4 shows the concept of this method.

Direct Substitution Method suffers from a serious problem. That is the calculation speed. If we limit the searching range with 100 cm for each dimension with 1-cm grid, and there are 3 receivers have been selected for estimating position of object, for 3D estimation the program must iterate about 100 x 100 x 100 x 3 = 3,000,000 times to complete all substitution actions. Thus, program will spend too much time for substituting and calculating. As the number of MD increases, the real time tracking may hardly being accomplished.

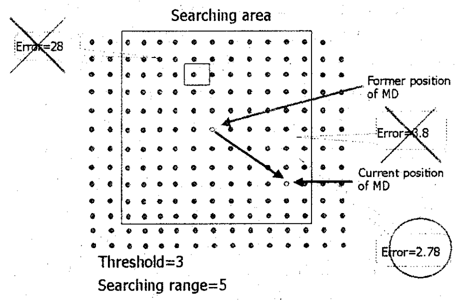


Fig. 4 Direct substitution method

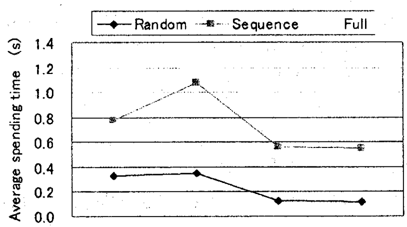


Fig. 5 Comparison of three substitution algorithms

There are three kinds of substitution algorithm - full, sequence and random substitution methods. Full substitution method substitutes all points in the searching area into calculation procedure, and then choose the point with least error as the answer. Sequence substitution method substitutes points in sequence, if the error is lower than the threshold that is set in advance, then this point is picked as answer. Random substitution method substitutes points in random mode. It randomly selects a point and substitutes it into calculation procedure, if the error is lower then threshold, picks this point as answer. The average calculation time of three methods at the same condition is shown in Figure 5. It shows that the random substitution method is more effectively.

The accuracy of the tracking system has its limit and we can tolerate a certain degree of error in location-aware system. Thus, we may not really need the position that calculated with the least error. Instead, the one with the error that is smaller than the value we can tolerate is also acceptable if the calculating time can be shortened. An improving way for increasing searching time will be considered in our future work.

For increasing searching speed of Direct Substitution Method, random point selection is applied. Setting an error threshold that can be accepted by location-aware system in advance. Randomly choosing a point at one time and substituting it into equation, then calculating the error and comparing the error with the threshold. If the error is smaller than the threshold, stopping the substitution action. Thus, the point can be regarded as position of object. By using random point selection method, direct substitution method will not substitute all points in searching area into equation and thus the searching speed can be increased.

4. Evaluation Result

4.1 Static Object Position Measurements

Figure 6 shows implemented MD and receiver. Static object position measurements were done in two test regions with distinct placing distance of receivers. To determine the accuracy of the tracking system, the position of an MD placed at known points is measured. Each point was measured 20 times at three different heights to get the average position estimating error of the point.

In the test region 1, a 5 x 5 grid of points, with grid spacing roughly 15cm was laid out on a table in the area where the ultrasonic tracking system was installed. Three receivers were placed on the ceiling 60cm apart. The positions of the points relative to the ceiling were measured by using a tape measure. Figure 7 shows the 3D graph of average error of each point in test region 1. In Figure 7, it is clear that the tracking system can be accurate to within 9cm in 3D position.

In the test region 2, a 6 x 10 grid of points with grid spacing 25cm was used for evaluating the accuracy of tracking system. Four receivers were place on the ceiling. Figure 8 shows the 3D graph of average error of each point in the test region 2. The average error of the tracking system measured in this region is around 8~10cm.

4.2 Mobile Object Position Measurements

Besides the static object, position measurement for mobile object was also evaluated. We took the MD moving with a trace that was designed in advance, and then compared the trace that measured by tracking system with the one

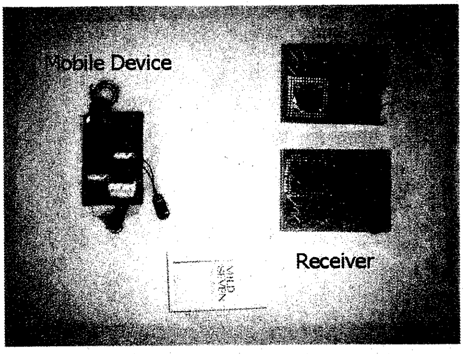


Fig. 6 Mobile Device and Receiver

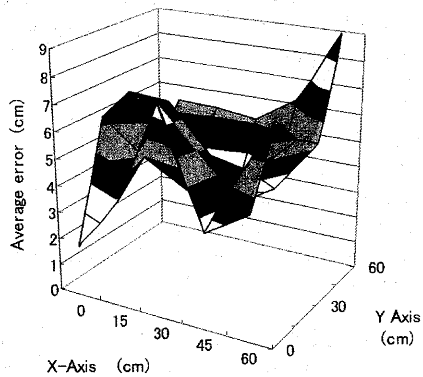


Fig. 7 Average error in the test region 1

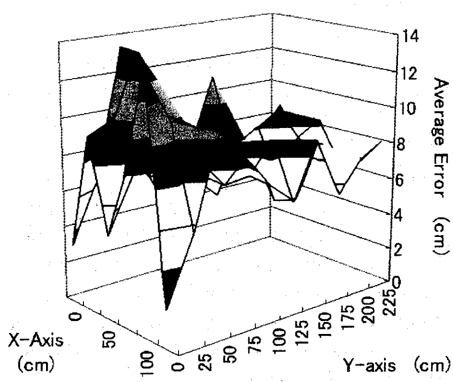


Fig. 8 Average error in test region 2

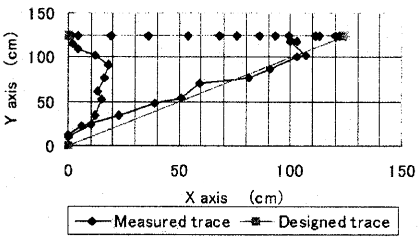


Fig 9 Tracking result in triangular pattern

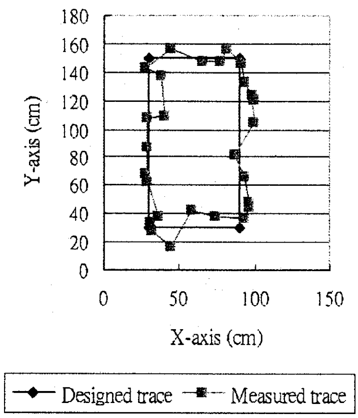


Fig. 10 Tracking result in rectangular pattern algorithms

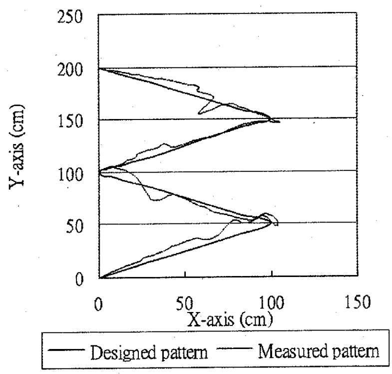


Fig. 11 Tracking result in curved pattern

designed in advance. Some moving patterns were made and used for evaluating the tracking system. Thus, the tracking characteristic of the tracking system can be found and evaluated.

Triangular Pattern

A triangle that started from origin to the right margin of x-axis, then moved to the left margin of x-axis and finally returned to the origin. The comparison of two traces is shown in Figure 9.

Rectangular Pattern

Rectangular moving pattern was also applied to evaluate the tracking ability of the tracking system. The rectangular pattern started at (30,30), then horizontally moved to (90,30), vertically moved to (90,150), horizontally moved to (30,150) and finally returned to (30,30). Figure 10 shows the result trace that the tracking system tracked.

Curved Pattern

Curve moving pattern started from origin, then three U-turns were applied in the pattern. Tracked pattern is shown in Figure 11. The tracking system also performed well in this pattern.

5. Conclusion

In this paper, we have argued that location-aware computing is indispensable to the implementation of context-aware computing system. Unlike the recent location-aware computing researches focusing on a particular scenario, our design on the location-aware computing system focuses on a generic environment. We had implemented and evaluated our location-aware computing system on the home and office environments. During the implementation of such system, we have introduced three entities - the Mobile Devices (MDs), the receivers, and the Mobile Device Manager (MDM).

In the design of our system, we have proposed the multilateration positioning system. We have also stated the attentions have to be paid and the measures have to be taken when applying the multilateration positioning design in our system.

As we assumed that the user carrying MD moves slowly in a home or office environment, when determining the user present location, we have introduced Direct Substitution Method. We explained three types of substitution ways in this Direct Substitution Method - the full substitution way, the sequence substitution way, and the random substitution way. We have compared the efficiency of these three ways, and we utilized the most efficient way, which is the random substitution way in our implementation system.

Lastly we have proved our system's suitability using in an indoor environment by showing the deviation in measurement is around 8cm to 10cm.

We have also showed the effectiveness of our system by carrying out several experiment tests in various environments with different conditions. We are convinced that our system is as good as the present researched location-aware computing systems and can integrate well with them.

However, there are still some improvements and further work we have to make in order to make the system can be practically used. Although we have successfully achieved a deviation of 8cm to 10cm our measurement, we tend to improve accuracy in measurement in order to elevate the reliability of our system. In the present time, the receivers in our system are connected with a 10Mbps ethernet cables. We plan to introduce 100Mbps ethernet cables or even fiber optic in our system in future, in order to provide a fast transmission of data between receivers and data-processing PC and thus improve the real-timeness of our system. The integration of our system and the outdoor GPS system is also the work remained.

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