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# Design and Implementation of a Fully Distributed Ultrasonic Positioning System

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## SUMMARY

In the ubiquitous computing environment, the physical locations of persons and goods are extremely important information. In this paper, the design of a fully distributed localization system based on ultrasound, mainly for the indoor environment, is described. This system performs localization with as few positioning references as possible by an iterative technique. When such a localization method is used, deterioration of localization accuracy due to no-line-of-sight signals and to accumulated errors is a problem. In this paper, the resolution of these problems is discussed and system evaluation by implementation experiments is carried out. With 24 devices, localization with an accuracy of about 20 cm is demonstrated. © 2007 Wiley Periodicals, Inc. Electron Comm Jpn Pt 3, 90(6): 17–26, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ecjc.20249

**Key words:** ubiquitous computing; localization; fully distributed system.

## 1. Introduction

One of the attractive applications of ubiquitous computing is the smart space. In the smart space, various services reflecting the real space situations obtained from sensor groups connected to a computer network embedded in the indoor environment are provided.

The provision of such services with real spatial orientation is one of the characteristics of ubiquitous computing. However, techniques for detecting the positions of people or goods play an extremely important role in handling the space information on a computer. The reason is the following. When real space information, ranging from basic information on temperature and humidity to sophisticated information such as the condition of humans, is handled, it is necessary to consider the relationship with positional information. For instance, if one considers temperature, the information that "the temperature is 25°" is not sufficient. Positional information indicating the location of the sensor that measured this temperature is needed. This situation is applicable to the condition of humans. For instance, the simple information "is walking" is not useful information. In general, it is necessary to understand where the person is walking.

For positional detection, GPS (Global Positioning System) can be used outdoors. However, most of the applications of ubiquitous computing assume indoor situations. Therefore, how localization can be performed indoors, where GPS cannot be used, is an important research subject in the ubiquitous computing field.

Various indoor localization systems have been proposed to date in order to address the above problem [1]. Depending on the localization method used, each system has advantages and disadvantages. There is no system that can be used for all applications under all environmental conditions. From the point of view of usability and localization accuracy, it is preferable to use a system that performs localization by TOA (Time of Arrival) or TDOA

(Time Difference of Arrival) using the propagation delay time of electromagnetic waves, based on a principle similar to that used in GPS. However, when indoor localization is performed by TOA or TDOA using electromagnetic waves, the propagation delay time of the wave corresponding to several meters must be measured. Hardware devices that can detect time differences of subnanosecond order or smaller are needed. In the future, due to the evolution of UWB (ultra-wideband) technologies, indoor localization systems based on electromagnetic waves that are capable of an accuracy of several tens of centimeters are expected. At present, ordinary researchers have no access to such hardware. Therefore, in research on indoor localization systems using electromagnetic waves, the mainstream is to use methods for localization based on the received wave intensity. Therefore, the localization accuracy is of the order of several meters.

On the other hand, in the field of ubiquitous computing, localization systems using ultrasonic waves that can achieve high accuracy with simple hardware have been developed. Although systems using ultrasonic waves have the limitation that localization is not possible if sound waves cannot reach the location due to screening objects, localization accuracy of a few centimeters can be accomplished rather easily if several sensors are used. The detection speed and system size are reasonable.

Active Bat [2] developed by Ward is a pioneering research project on a localization system using ultrasonic waves. In Active Bat, a centrally controlled ultrasonic wave receiver array is placed on the ceiling surface. The ultrasonic waves from a small mobile device with an ultrasonic transmitter are received by the receiver array. The ultrasonic receiver array and the mobile device are synchronized by a wireless connection. The time required for an ultrasonic pulse transmitted from the mobile device to arrive at each ultrasonic receiver (propagation delay time) is measured. By multiplying the measured propagation delay time by the speed of sound, the distance between the mobile device and each of the ultrasonic receivers is derived. Since the locations of the individual receivers are accurately given beforehand, the location of the mobile device can be derived three-dimensionally by solving a set of simultaneous equations involving the measured distance to each receiver and the locations of the receivers.

The positioning principle of Cricket [3], developed by Priyantha and colleagues, is identical to that of Active Bat. However, while Active Bat uses centralized control, autonomous distributed control is used in Cricket. Ultrasonic receivers are placed on the ceiling in Active Bat, whereas ultrasonic transmitters are placed on the ceiling in Cricket. The locations of the transmitter array are assumed known. These transmitters randomly send ultrasonic pulses and also send information on the coordinates of the transmitters and synchronization signals. A wireless receiver and an ultrasonic receiver are embedded in devices worn by persons or attached to objects. On the device side, the distance to the transmitter is measured and the position is determined.

Although both Active Bat and Cricket are well-designed systems, there is a significant problem in using these systems outdoors. In principle, Active Bat and Cricket require ultrasonic receivers or transmitters whose accurate positions must be known in localization operations (below, they are called “initial references”). For instance, in Active Bat, it is necessary to install the ultrasonic receivers used as initial references with a spacing of about 1.5 m on the ceiling in order to perform accurate localization. Since the propagation distance of ultrasonic waves in air is only a few meters and the ultrasonic transmitters have directivity, the ultrasonic waves from the transmitters must be received constantly by a sufficient number of receivers for localization calculations. Therefore, when Active Bat is introduced in a room 10 m square, the locations of about 50 receivers must be measured accurately beforehand. If such a system is introduced into an office building, the number of initial references is enormous and the deployment scalability of the system is severely limited.

In contrast, many methods for determination of many sensor nodes while using as few initial references as possible have been proposed in the field of sensor networks. In particular, the iterative multilateration [4] proposed by Savvides and colleagues determines locations iteratively by using the nodes whose positions are identified by the initial references as new references. This is considered an excellent idea to reduce the setup cost of the initial references described above. From this point of view, the present authors have performed research on a fully distributed indoor localization system DOLPHIN (Distributed Object Localization System for Physical-space Internetworking) [5, 6] in which indoor localization is realized with as few initial references as possible, based on the idea of iterative multilateration. The difference of the present research from that of Savvides is the following. The research by Savvides is based on simulations focusing on efficient localization and low communication cost. The research by the present authors is an attempt to resolve various problems that realistically arise in the application of the idea of iterative multilateration to an ultrasonic localization system in an experimental approach [6].

In this paper, the design, installation, and evaluation of DOLPHIN are described. In Section 2, the system configuration and basic localization algorithm for DOLPHIN are explained. In Section 3, solutions to the two significant problems of error accumulation and “No-Line-of-Sight” that arise in the application of DOLPHIN to a real environment are presented. Section 4 describes an evaluation with 24 devices. Conclusions are presented in Section 5.

## 2. System Configuration

Figure 1 presents the system configuration of DOLPHIN, which is a fully distributed system consisting of several DOLPHIN nodes. Each DOLPHIN node has an ultrasonic transceiver function, a wireless transceiver function, and an operating function to perform measurements (see Fig. 2). In DOLPHIN, these node sets are fully distributed in control, so that iterative multilateration as an iterative position determination procedure is possible. At the lower left in Fig. 1, Nodes A to C are the initial reference nodes whose locations have been accurately measured. Nodes D to F are undetermined nodes. Node D can receive all of the ultrasonic waves transmitted from initial reference nodes A to C directly, but not all of them can be received by Nodes E and F due to shielding by the walls. In this situation, Node D measures the distances to the initial references A to C using ultrasonic waves, so that its own location is identified. Node D, whose location is now identified, becomes a new reference node. Once Node D becomes a reference node, Node E can determine its location by using Nodes B, C, and D, so that it becomes another new reference node. Similarly, the location of Node F can be determined by means of Nodes B, D, and E. In this way, by using a few initial reference nodes whose positions must be measured manually, the locations of all other nodes can be determined iteratively. This is the basic idea of iterative multilateration. It is evident from this example that the ability to determine the locations of devices that cannot receive ultrasonic waves directly from the initial nodes exists in iterative multilateration. This is an advantage of the method in applications to localization.

Figure 3 presents an algorithm for specific realization of the iterative multilateration by DOLPHIN nodes. In DOLPHIN, the node set composing the system alternately performs three functions, “master node,” “transmitter node,” and “receiver node” for localization. The only nodes that can be master nodes or transmitter nodes are reference nodes whose locations have been determined. Let us consider, as shown in Fig. 3(a), that the situation in which

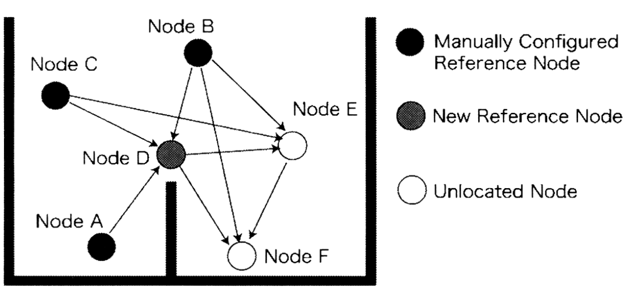



Fig. 1. System architecture.

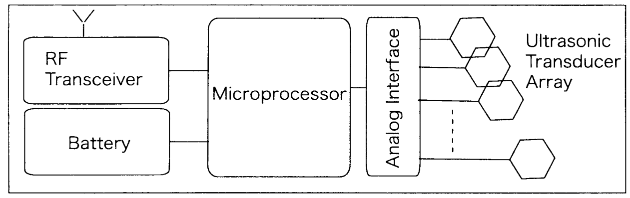



Fig. 2. Node architecture.

Nodes A to C are the initial reference nodes and Nodes D to G are undetermined nodes is the initial state. DOLPHIN starts the process from this initial state and activates the localization algorithm by the bootstrap process. The objective of the bootstrap process is that each node knows the initial referenced nodes. In the bootstrap process, the message identifying the initial reference nodes (Nodes A to C in this example) is broadcast by a wireless transceiver with random timings. The node IDs and locations are contained in this message. Each node that receives this message records the node IDs and locations in the “Reference Node List.” These IDs are unique within the system. After sufficient time has passed, one of the initial reference nodes spontaneously becomes the master node with a random timing.

In DOLPHIN, the master node acts as the time reference for measurement of the distance between nodes by the ultrasonic wave. Let us here consider the case in which Node B is the master node, as shown in Fig. 3(b). Node B

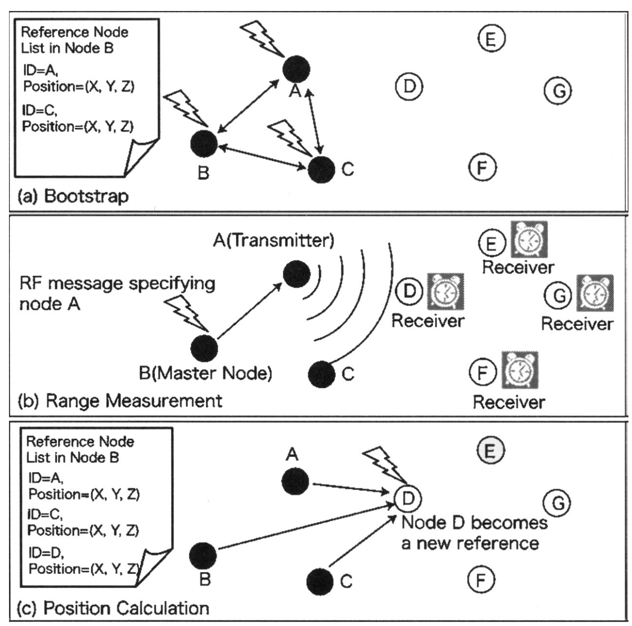



Fig. 3. Distributed localization algorithm.

first uses its wireless transceiver to notify its neighbors that it has become the master. Each node that receives this message completes the bootstrap process and shifts its process to localization. Subsequently, Node B randomly selects from the reference node list that it maintains a node to be the transmitter node. Let us here consider the case in which Node A becomes the transmitter node. Node B transmits by wireless a measurement message, indicating the sending of the ultrasonic pulse. Then, since the measurement message is transmitted by wireless, nodes C to F in addition to Node A can also receive this message. Node A sends out an ultrasonic pulse immediately upon receipt of the measurement message. Nodes C to F activate the counters contained in their microprocessors, initiating the time count. Nodes C to F stop counting if the ultrasonic wave sent out from Node A is received and determine the propagation delay time of the ultrasonic wave. When this delay time is multiplied by the speed of sound, the distance to Node A can be obtained. Finally, Node A publicizes its location by wireless so that Nodes C to F can receive information on the coordinates from which the ultrasonic wave is transmitted. In the above process, it is assumed that the propagation delay time of the wireless signal is negligible in comparison with the propagation delay time of the ultrasonic wave. It is also assumed that the time required for reception of the message is constant at all nodes. Also, the nodes in DOLPHIN contain temperature sensors, so that variations of the speed of sound due to temperature can be taken into account when determining the distance from the propagation delay time.

In the next cycle, Node A acting as the transmitter node becomes the master node and distance measurement is performed by a similar procedure. After sufficiently many measurement cycles, Node D is considered to have completed distance measurement from sufficiently many nodes for position determination. Node D then determines its location by triangulation. In addition, Node D reports by wireless that it can now operate as a new reference node. After receiving this information, the reference node set (Nodes A to C in this example) will add Node D as a reference node, which will be recognized as a candidate for the transmitter node.

By repeating the above operation, the locations of Nodes D to F are iteratively determined. Note that if node damage or communications impairment takes place, the algorithm ceases to operate. In this case, each node detects that the measurement message has not been transmitted within a certain time and one of the reference nodes becomes a master node at random in a manner similar to the bootstrap process, so that the algorithm continues. In the example described in this section, the position is derived by measuring the distances from three nodes in order to simplify the explanation. The number of nodes needed for position determination is generally at least four.

## 3. Accuracy Enhancement

As described in Section 2, the number of initial references can be reduced by applying iterative multilateration to a localization system based on ultrasonic waves. In reality, to achieve accuracy of localization it is necessary to resolve two problems, error accumulation and the “No-Line-of-Sight” signal problem. These two problems and their solutions are described below.

### 3.1. Error accumulation problem

Figure 4 shows a specific example of the error accumulation in iterative multilateration. In this example, Nodes A to D are the initial reference nodes and Nodes E and F can receive ultrasonic waves from these initial references. First, based on the algorithm described in Section 2, the case is chosen in which Node E determines its own location. No matter how accurately the coordinates of the initial references are determined, measurement errors are necessarily present in the measured distances to initial references A to D. Therefore, Node E determines its own location in a form containing these measurement errors (this is the problem of accumulation of errors). Although Node E becomes a new location reference at the stage of position determination, the accuracy as the reference is degraded in comparison with initial references A to D. Next, suppose that Nodes A, B, D, and E are used when Node F determines its own location. In this case, in addition to the measurement errors from Nodes A, B, D, and E, Node F also accumulates the error stored by Node E. As the measurement algorithm is performed, the error stored by Node F is likely to be stored again by Node E. As a result, the position errors increase exponentially at Nodes F and E as time progresses. In this example, two nodes E and F are considered. However, this problem becomes more severe as the number of undetermined nodes increases.

Error accumulation by itself is fundamentally an unavoidable problem. However, the problem of iterative error accumulation must be avoided. Hence, for the reference nodes, a metric indicating their accuracy as a reference is introduced. A method is developed to select the reference

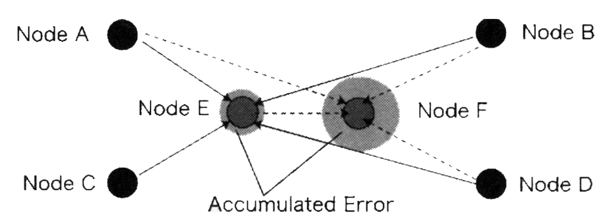



Fig. 4. Error accumulation problem.

node on the basis of the metric before a node without a determined location makes a decision.

Let us consider a model in which Node E determines its location by means of the reference nodes A to D. As described above, Node E measures the distance to reference nodes A to D for localization. Hence, this distance measurement is modeled as shown in Fig. 5(a). At the *i*-th measurement, the measured distance $r_i$ between the reference point (specifically corresponding to Nodes A to D) and the measurement point (specifically Node E) is expressed as

$$r_i = r_0 + \epsilon_{pi} + \epsilon_{ri} \quad (1)$$

Here $r_0$ is the true distance between the reference point and the measurement point, $\varepsilon_{pi}$ is the position error of the reference point, and $\varepsilon_{ri}$ is the measurement error in the measurement process. If there is no correlation between the position error $\varepsilon_{pi}$ and the measurement error $\varepsilon_{ri}$, the variance of the distance measurements, namely, the localization error $\sigma^2$, is given by

$$\sigma^2 = \sigma_p^2 + \sigma_r^2 \quad (2)$$

if a sufficient number of measurements are made. In the above, $\sigma_p^2$ is the variance of the position error of the reference point and $\sigma_r^2$ is the variance of the measurement error. If localization is performed with the model shown in Fig. 5(b), the position error $\sigma_{pE}^2$ of Node E is expressed as follows by means of the concept of PDOP (Position Dilution of Precision) [7]:

$$\sigma_{pE}^2 = PDOP^2 \times \sigma_{UERE}^2 \quad (3)$$

Here *PDOP* is a value determined only by the geometrical distribution of the four nodes used as references and is a parameter indicating the magnitude of the localization error. $\sigma_{UERE}^2$ is the User Equivalent Range Error [7] and is expressed as follows based on the error propagation rule:

$$\sigma_{UERE}^2 = \sqrt{(\sigma_A^2)^2 + (\sigma_B^2)^2 + (\sigma_C^2)^2 + (\sigma_D^2)^2} \quad (4)$$

In the above, $\sigma_A^2$, $\sigma_B^2$, $\sigma_C^2$, and $\sigma_D^2$ are the localization errors of Node E relative to the reference nodes A to D. If it is assumed that $\sigma_A^2 = \sigma_B^2 = \sigma_C^2 = \sigma_D^2 = \sigma^2$ $(= \sigma_p^2 + \sigma_r^2)$, then the position error $\sigma_{pE}^2$ of Node E is

$$\sigma_{pE}^2 = PDOP^2 \times \sqrt{4}(\sigma_p^2 + \sigma_r^2) \quad (5)$$

The variance $\sigma_r^2$ of the measurement error depends on the hardware of the measurement setup. If all nodes are assumed to have hardware of the same quality, this variance is assumed constant for all measurements. However, since the variance of the position error for Nodes A to D varies depending on the reference node used for position determination, it is not possible in general to assume that $\sigma_p^2$ is constant. Hence, the variance of the position errors for Nodes A to D is taken as $\sigma_{pA}^2 - \sigma_{pD}^2$. Then, $\sigma_p^2$ is determined from their weighted mean square error:

$$\sigma_p^2 = \frac{w_A\sigma_{pA}^2 + w_B\sigma_{pB}^2 + w_C\sigma_{pC}^2 + w_D\sigma_{pD}^2}{\sqrt{w_A + w_B + w_C + w_D}} \quad (6)$$

$$w_A : w_B : w_C : w_D = \frac{1}{\sigma_{pA}^2} : \frac{1}{\sigma_{pB}^2} : \frac{1}{\sigma_{pC}^2} : \frac{1}{\sigma_{pD}^2}$$

$\sigma_{pE}^2$ derived in this manner is used for determination of the metric $E_E$ for Node E as follows:

$$\begin{cases} E_E = 1 - \sigma_{pE}^2/\sigma_{th}^2 & (\sigma_{pE}^2 < \sigma_{th}^2) \\ E_E = 0 & (\sigma_{pE}^2 > \sigma_{th}^2) \end{cases} \quad (7)$$

Here, $\sigma_{th}^2$ is a design parameter providing the threshold of the allowed position error. By using this equation, it is possible to provide a metric value to the reference node in such a way that the value decreases in each generation from the value of unity for the initial reference, which has the highest accuracy. All nodes that could be position references calculate their own metric values, which are reported to the neighbors by means of wireless transceivers. When a certain node intends to determine its position, the nodes with the highest possible metric values are used as the references. Specifically, when a certain node receives ultrasonic waves from more than four nodes in order to calculate the distances to these nodes, the position determination is performed by means of a triangulation equation based on the four nodes with the highest metric values. In selecting the references on the basis of the metric, a method is conceivable in which the most accurate position determination is performed by considering PDOP in addition to the metric. However, since the computational effort is increased in reference selection, only the metric is used in the present system.

By the method described above, the problem of degradation of localization accuracy due to iterative error accumulation, which is considered severe in DOLPHIN, can be avoided.

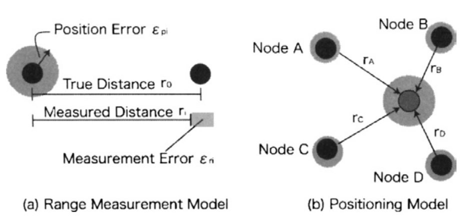



Fig. 5. Error accumulation model.

### 3.2. "No-Line-of-Sight" signal problem

The second realistic problem encountered by DOLPHIN is the problem of No-Line-of-Sight (NLOS) due to reflection of ultrasonic waves. In general, diffraction and reflection of ultrasonic waves take place frequently in an indoor environment. Thus, as shown in Fig. 6, the arriving line-of-sight ultrasonic waves are blocked by obstacles and only reflected waves or diffracted waves will arrive. In such cases, measurement of the distance between the node sending out the ultrasonic wave and the node receiving it is no longer performed correctly, and the position detection accuracy is significantly degraded. This problem, in which line-of-sight ultrasonic waves are blocked and only diffracted waves or reflected waves arrive, is called the NLOS problem.

In general, in an indoor localization system using ultrasonic waves, the effect of reflected waves is more severe than that of diffracted waves. The ultrasonic waves used in indoor localization systems often have a frequency of 40 kHz. Thus, the wavelength is about 9 mm. Hence, no diffraction of ultrasonic waves takes place for an obstacle with a size of more than 9 mm due to the physics of diffraction. Also, as shown in Fig. 6, if the distance measurement errors due to diffracted waves and reflected waves are considered, the propagation distance of the reflected wave is longer. Therefore, the NLOS signal with a significant impact on distance measurement is mainly the reflected wave. Hence, in this paper, a solution for the NLOS problem is considered in terms of reflected waves.

The problem of NLOS signals due to reflected waves has been treated by Ward, who designed Active Bat [8]. In his method it is assumed that the reflected wave intensity is lower than the direct wave intensity due to attenuation in the course of propagation and reflection. Based on this assumption, waves with weaker received signals are detected as reflected waves by using the relationship of the signal strength and the distance measured in advance. Since this method can easily be realized, the present authors initially adopted this method in DOLPHIN. However, we concluded that treatment of waves with weak signal strengths as reflected waves is not adequate because ultrasonic waves are subject to interference in an indoor environment.

The authors have conceived a method of detecting reflected waves by a geometric procedure. In addition to the method of Ward, the reflected wave can now be detected geometrically. Figure 7 shows the method of detection of reflected waves by the geometric method. In this method, it is assumed that the node can estimate the angle of arrival of the ultrasonic wave by means of an ultrasonic transducer array (in the implementation experiment described later, rough angle estimation is performed on the basis of the signal strengths detected by individual transducers in the ultrasonic transducer array). Let us now assume that Node R measures the distance between reference nodes O and P. Then, while Node R can receive a direct wave from Node O, only the reflected wave from Node P can be received due to an obstacle. If it is assumed that Node R can estimate the direction of arrival of the ultrasonic wave, then the difference in the angles of arrival $\theta_{ORV}$ of the ultrasonic waves from Nodes O and P can be obtained. Looking from Node R, Node P appears to be located at the location of Node V. Hence, let us consider the distance $d_{OV}$ between Nodes O and V. If the measured distances from Node R to Node O and Node P are $r_O$ and $r_P$, then $d_{OV}$ is

$$d_{OV} = \sqrt{r_O^2 + r_P^2 - 2r_O r_P \cos\theta_{ORV}} \quad (8)$$

Further, Node R can acquire the present coordinates of Nodes O and P broadcast by the wireless transceiver. As a result, the distance $d_{OP}$ between Nodes OP can be calculated. If $d_{OV}$ and $d_{OP}$ are compared, the location of the reflected wave can be detected. If $d_{OV}$ and $d_{OP}$ have similar values, the wave is considered to be a direct wave. On the other hand, if their values are substantially different, it is considered to be a reflected wave.

Although the above procedure can detect the existence of a reflected wave, it is not possible to determine whether the ultrasonic wave from Node O or that from Node P is the reflected wave. For this reason, discrimination is usually performed from the measured distances from more nodes. In the present system, if a measured distance is judged to be caused by an NLOS signal, the node does not

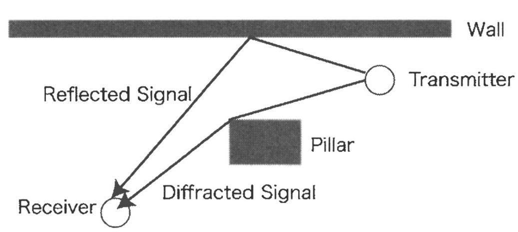



Fig. 6. No-Line-of-Sight signal.

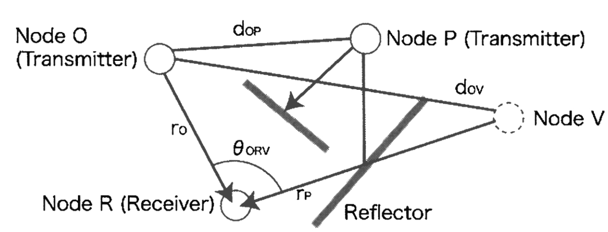



Fig. 7. Geometry-based NLOS signal estimation.

use this particular measured result for calculation of the location.

What difference is sufficient to identify an NLOS signal depends on whether localization probability or position detection accuracy is emphasized, and on the number of obstacles causing NLOS signals and the node density. It is difficult to discuss a general determination method. For instance, in an environment with many obstacles, NLOS signals are more likely to be received. Therefore, the value is set smaller so that the probability of the localization with an NLOS signal remains low. However, when the node density is not sufficient, a sufficient number of distance measurements for localization cannot be obtained and the probability that some nodes cannot determine their positions is increased. If the probability of position detection must be improved at the cost of somewhat lower position detection accuracy, it is more advantageous to use a larger value.

In the present system, the value used for judgment was empirically set. In locations where the number of obstacles was large (near the wall or shelf), the value used was about 10 cm. Where there were few obstacles (such as ceiling surfaces), the value was about 30 cm.

## 4. Implementation and Evaluation

In order to present the concept of the DOLPHIN system and to studying its basic performance, an experiment was performed by implementing 24 nodes as shown in Fig. 8. The experiment compared the case with only iterative multilateration, using a 1.8 m × 1.8 m × 1.0 m desktop test bed, and the case with an added provision for the error accumulation problem and the NLOS signal problem. Subsequently, 24 nodes were placed in a laboratory measuring 3.6 m × 3.6 m × 2.4 m and the performance in a real environment was studied. In each of the experiments on the desktop test bed and in a real environment, the value of $\sigma_{th}^2$ set in the algorithm to avoid the iterative error accumulation described in Section 3.1 was set to 50 cm. The accuracy of angle estimation in the algorithm for detecting the NLOS signal described in Section 3.2 was 45° and the judgment threshold was 10 cm.

Figure 9 shows the experimental results for the desktop test bed. In this experiment, 10 nodes, Nodes A to J, were placed in the layout shown in Fig. 9(a). Of these, four nodes, A–D, were placed on the four corners of the table as reference devices. In addition, three acrylic plates for generating NLOS signals were installed. Under these conditions, the accurate positions of Nodes E to J were measured beforehand. The localization accuracy was compared when only iterative multilateration was used and when provisions for dealing with error accumulation and NLOS signals were implemented. In the evaluation of the localization accuracy, the position error was derived from 100 measurements. Based on this result, the cumulative distribution function was calculated and the error at which the function value was 95% was used (hence, the localization results had a 95% probability of being within a circle centered at the true coordinate with a radius given by the error value.

Figure 9(b) shows the experimental results. It is clear that the localization accuracy is a few tens of $cm^{-1}$ or more due to error accumulation if only iterative multilateration is used. In particular, significant errors are found even if Nodes E and F can directly receive signals from the four initial reference nodes. We investigated which node was used as the reference for localization performed by Node F and found that Node J was used. This node was intentionally placed at a location where the NLOS signal was likely to be received by the acrylic plates. Hence, the accuracy was poor when this was used as the reference. As a result, the error of Node J was propagated and accumulated at Nodes E and F, generating significant errors.

In contrast, when a similar experiment was carried out using nodes with provisions against error accumulation and the NLOS signal problem, the localization error was

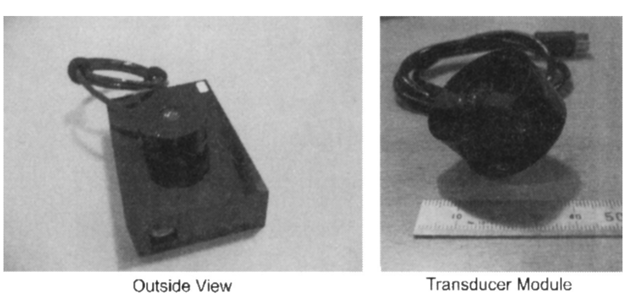
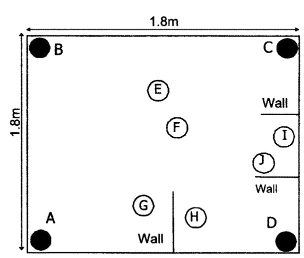


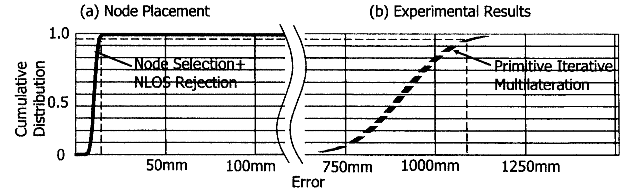

Fig. 8. Hardware implementation.




(a) Node Placement

| Node | Positioning Error [mm] (95% CDF) | |
|---|---|---|
| | Primitive Iterative Multilateration | Node Selection+ NLOS Rejection |
| E | 980 | 24 |
| F | 1090 | 17 |
| G | 380 | 24 |
| H | 550 | 13 |
| I | 530 | 18 |
| J | 970 | 43 |

(b) Experimental Results




(c) Example Cumulative Distribution Function of Node F

Fig. 9. Experimental result in desktop testbed.

less than 5 cm. It is clear from the cumulative distribution function of Node F that the localization error has a value close to the original accuracy of the localization system with ultrasonic waves and that the results are excellent. Even if a provision is made for the NLOS signal problem, the localization accuracy for Node J, for which NLOS signals are easily received, is worse than for the other nodes. This is because the estimation of the angle of arrival of the ultrasonic waves by an ultrasonic wave transducer array is performed with a coarse resolution of 45°. Hence, not all NLOS signals may be detected.

Next, as shown in Fig. 10(a), 24 nodes were placed within a laboratory 3.6 m square and the localization performance in a real-world environment was studied. In this experiment, the influence of the number and orientation of the initial reference nodes on the position detection accuracy was studied for three cases, in which the initial reference nodes were placed in the following ways: (a) four on the corners of the ceiling, (b) four near the center of the ceiling, and (c) six near the center of the ceiling. In each experimental setup, the nodes used had provisions against error accumulation and the NLOS signal problem. A total of 100 measurements were performed for all nodes. As in the experiment with a desktop test bed, the localization error was derived from the cumulative distribution function and the average was calculated.

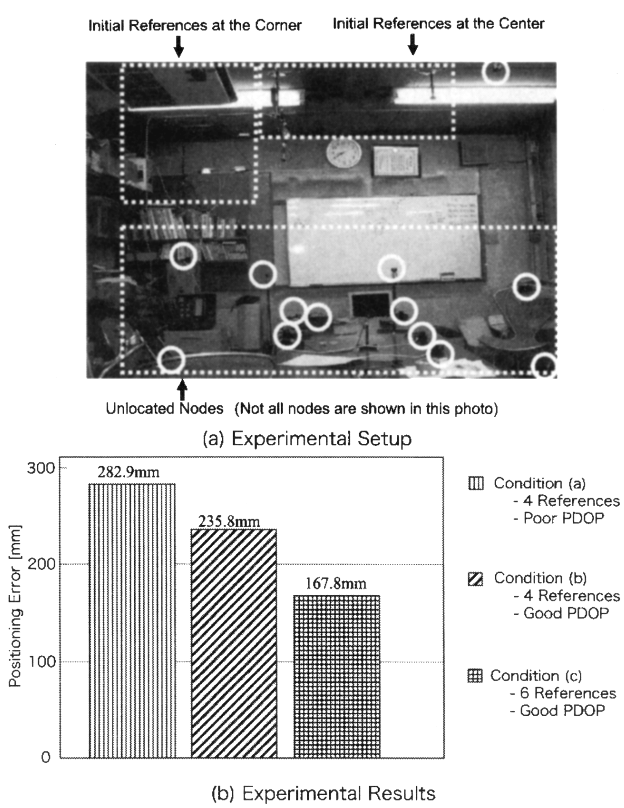



Fig. 10. Experimental result in room environment.

The experimental results are shown in Fig. 10(b). It can be seen that the errors are about 28 cm in (a), about 24 cm in (b), and about 17 cm in (c). When the PDOP is derived for case (a), a value greater than 10 is obtained at each node. Hence, because the geometrical orientation is poor for the initial reference nodes in (a), the distance measurement error is amplified and the error becomes significant. On the other hand, since the initial reference nodes are placed at the center of the room, an improvement of the PDOP is expected. It is confirmed that the position determination is more accurate than that in (a). Further, in case (c), more nodes can perform position determination at a good PDOP due to an increased number of initial reference nodes. Therefore, the position determination is more accurate than in cases (a) and (b).

It is evident from this experiment that the localization accuracy is significantly affected by the choice of the location of the initial reference nodes and the number of nodes when the system is operated in a real environment. Although it is difficult to derive optimum locations and numbers in general, it was empirically found in the experiment that relatively accurate measurement location tends to be achieved if the initial reference nodes are placed so as to have the most homogeneous density possible in the space.

In contrast to the ability of Active Bat to realize an localization accuracy of about 3 cm, that of DOLPHIN is somewhat less than 20 cm. In terms of localization accuracy, Active Bat is superior. The principal reason is error accumulation during iterative localization. As described in Section 3.1, iterative localization has the advantage of performing localization with a small number of references. On the other hand, the problem of error accumulation is fundamentally unavoidable. In comparison with such systems as Active Bat, its accuracy is necessarily decreased. Also, in Active Bat, all measured results are collected by the central server and the position can be calculated most accurately by taking account of the factors affecting localization accuracy such as PDOP. Since the algorithm in DOLPHIN is autonomously distributed, improvement of the localization accuracy is difficult. When further improvement of the localization accuracy is desired while still taking advantage of iterative localization, optimization by using a centralized control element such as the one in Active Bat is necessary.

## 5. Conclusions

In this paper, the design and implementation of DOLPHIN, a distributed localization system using ultrasonic waves, are described. Based on the iterative multilateration procedure, it is shown that a system for determining many nodes with a small number of initial reference nodes can be specifically realized. Also, a method is presented to reduce the error accumulation problem and the NLOS problem, which cause a substantial decrease in localization accuracy. Actually, in an implementation experiment using 24 nodes, a localization accuracy of about 17 cm was demonstrated.

The authors consider that the implementation and the experiment with DOLPHIN are successful in demonstrating the basic concept and its performance. On the other hand, assuring stable reception of ultrasonic waves is found to be extremely important from a practical point of view. For instance, when a person claps his hands or places an object on a desk, ultrasonic waves are generated and constitute a serious noise source for the system. In addition, the directivity and interference of the ultrasonic waves can limit the range and accuracy of localization. In order to achieve stable reception of ultrasonic waves, it is considered necessary to use a broadband transducer [9] and a signal processing technique such as modulation of the ultrasonic waves.

In order to emphasize distributed localization in DOLPHIN, the nodes were assumed stationary in this research. However, in the applications of ubiquitous computing, tracking of moving objects may be required. In such a case, it is necessary to consider approaches such as the use of Kalman filter in tracking [10]. In addition, future research will require the consideration of more practical approaches, including reduction of power consumption and miniaturization.

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