A GPS-Free Localization Scheme for Wireless Sensor Networks

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***Abstract*-Localization is an important and extensively studied problem in ad-hoc wireless sensor networks. Most schemes require some nodes functioned as anchors with positions configured manually which are error-prone. In this paper, a GPS-free localization scheme is proposed. High accurate TOA is acquired by means of measure the time difference between two simultaneously transmitted radio and ultrasonic signals at the receiver. With the assistant of coarse AOA information, the flip ambiguity is fixed. The performance of our scheme is demonstrated with an accuracy of a few centimeters using our prototype nodes.**

***Key words*- localization, wireless sensor networks, GPS-free**

I. INTRODUCTION

The recent advances in radio and embedded system technologies have enabled the proliferation of wireless micro-sensor networks (WSNs) [1]. Such wirelessly connected sensors are released in many diverse environments to perform various monitoring tasks. In many such tasks, location awareness is inherently one of the most essential system parameters [2].

Most of the current literature on location discovery in WSNs assumes some beacon nodes with known position [4-9]. Their locations are then used to determine the positions of other ordinary sensor nodes. Manual measurement and configuration methods for obtaining location don't scale and are error-prone, and equipping sensors with GPS is often expensive and does not work in indoor and urban environment.

Sensor networks can therefore benefit from a self-configuring method where nodes cooperate with each other, estimate local distances to their neighbors, and converge to a consistent coordinate system which has only translation freedom.

The Self Positioning Algorithm (SPA), which is used in distributed mobile wireless networks without GPS receivers, was proposed first by Capkun [10]. The disadvantage of SPA is that the communication cost and convergence time grow exponentially with the number of nodes since each node participates individually in the process of building and merging the local coordinate system.

To overcome the shortcomings of SPA, Cluster based SPA (CSPA) was proposed in [11]. In this method, the nodes are initialized with different roles: a small subset of the total number of nodes is selected to be master nodes and the others then become slave nodes. Every master node builds a local coordinate system with an algorithm similar to SPA, and two master nodes need two common slave nodes to merge their local coordinate systems. Compared to SPA, CSPA provides a considerable improvement by reducing communication overhead and convergence times and has been extended in the literature [12-14] to different applications. Unfortunately, the algorithm brings with it the flip ambiguity when merging local coordinate systems because two master nodes cannot be within the range of each other, the quadrilateral composed by two master nodes and two slave nodes is not a robust one [15-16].

For more details of the principles and characteristics of other relative localization algorithms, we refer the reader to Chen's good review [17]. Despite a significant number of relative localization approaches developed for WSNs localization, there are still many open issues in the area. One of the problems is that all these relative location algorithms are based on topological relations between two sensor nodes, and the flip and rotate ambiguity of the global coordinate system is left. This is by nature, for a planar coordinate system, is freedom to rotate and flip if there is no anchor to fasten it.

This paper describes a GPS-free localization scheme like the AFL algorithm [18] where nodes start from an initial coordinate assignment and converge into a topology that resembles the true configuration. The key idea in this paper is flip-free. With the assistant of coarse AOA information, the initial and the global flip ambiguity are eliminated.

Through extensive simulations under a variety of node densities we show that our algorithm is superior to previously proposed methods, in terms of its ability to compute correct coordinates under a wider variety of conditions and its robustness to measurement errors.

II. NODE DESIGN

To perform evaluation of our scheme, we have designed and implemented a sensor node (figure 1). The node has to accomplish several tasks: communication with other nodes, estimate the range between the neighbors and tell the AOA, measure the direction that deployed. To coordinate all these activities, the node has been provided with a low power microcontroller which consumes less than 1mA in active mode and only 5uA in sleep mode. The microcontroller is interfaced with a radio transceiver working in the 433MHz band, 8 ultrasonic transducers and a digital compass. The

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microcontroller also controls a network of CMOS switches used to selectively disconnect the different parts of the node from the power source. As a consequence, the microcontroller is the only component drawing current from the power source in sleep mode. This results in very low power consumption in the quiescent state. After waking up, the microcontroller switches on the other parts of the node.

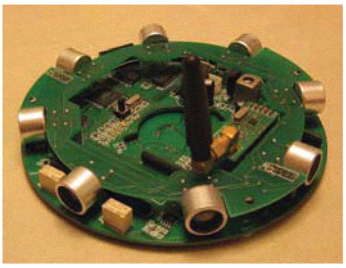

Figure 1. Prototype node.

A. *TOA measurement*

We get the TOA by means of measure the time difference between two simultaneously transmitted radio and ultrasonic signals at the receiver (figure 2) like [19]. The ultrasonic ranging extent of our nodes is about 10 meters. After adjusting the speed of sound used to calculate the distance by atmosphere temperature measurement, our ranging system can provide an accuracy of 2 centimeters for node separations fewer than 10 meters from 0 to 40 degrees Celsius.

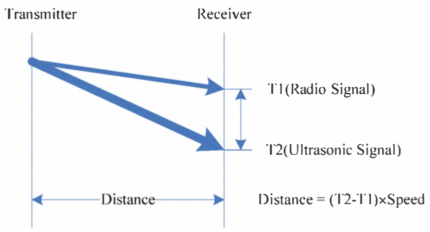

Figure 2. Distance measurement using ultrasonic and radio signals

B. *Coarse AOA measurement*

It's obvious that the performance of localization scheme can be improved if the node has the ability to estimate the AOA of the neighbor nodes. But it's less feasible because of the cost and the power consumption. In our scheme, we only detect the AOA approximately, that is, only which transducer receive the ultrasonic signal first is concerned and don't care about how much it's prior to the next one. Though it brings an error from -22.5 to 22.5 degrees to the AOA acquired, it's enough to determine the flip direction and, provided with 10 nodes or more, the global coordinate system with fairly high accuracy.

III. LOCALIZATION ALGORITHM

A. *Assumptions and Scheme Overview*

In this paper, we propose a GPS-free localization scheme for WSNs. We make the following main assumptions on our model, or our scheme is restrict to the following scenario:

- ♦ All nodes are stationary. So the network topology is fixed after deployed.
- ♦ There are no landmarks in the network. That is to say, no node has absolute location information.
- ♦ There are no anchors in the network. That is to say, no node has relative location information.
- ♦ All sensors are homogeneous, with the same technical characteristics, and especially the same transmission range of both ultrasonic and radio signals.
- ♦ All sensors use omnidirectional radio antennae.
- ♦ All the wireless links between sensors are bidirectional.

The whole process of our scheme consists of three phases: coordination phase, measure phase and localization phase. Prior to ultrasonic signal transmission, nodes participating in the localization coordinate with one another. At the end of this phase, a node is chosen to act as a coordinator. We call this node the master node, and the other nodes slaves. In the measure phase, the master node schedule which slave node send ultrasonic signal and when the phase ended. For a particular slave node, the ultrasonic signal transmission starts behind a radio notification message indicating that a particular measure process is about to begin. The receiver nodes of this radio notification message then begin waiting for the ultrasonic signal. After the ultrasonic signal is received, the range and the AOA information are sending to the master node. At the end of the measure phase, the master node has collected the direction of the all nodes, distance and AOA between any two neighbor nodes. In the last phase, the position is determined on the master node. The algorithm includes four steps: the construction of an initial coordinate system, iterative multilateration, mass-spring optimization, and last, the coordinate system rotation.

B. *Construction of Initial Coordinate System*

Because our scheme has no GPS installed, nor any anchor. The first step is to find a local relative position estimate, or the initial coordinate system. We use triangulation techniques. First of all, we find a triangle with maximum area among all the ones in the map made up with the ultrasonic connection as the initial anchors (Figure 3).

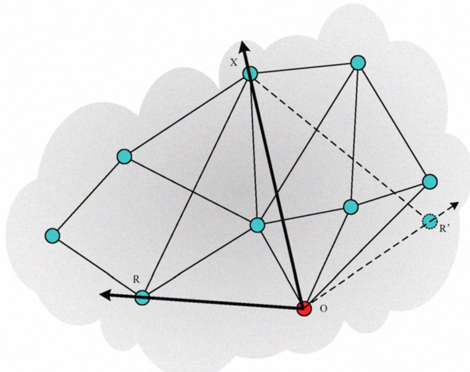

Figure 3. Construction of initial coordinate system

The node with the minimum id on the corner of this triangle assumes itself at the origin of the initial coordinate system and the node with lager id is selected to form the positive x-axis.

Hence, the position the nodes of O and X is given as follows:

$$P_0(O) = (0,0)$$
$$P_0(X) = (D(O,X),0)$$

The coordinate of $P_0(R) = (x_2, y_2)$ can be computed with respect to the x-axis formed by $\overrightarrow{OX}$ using the law of cosines as follows:

$$\cos(\theta) = \frac{d_1^2 + d_3^2 - d_2^2}{2d_1 d_3} \quad (1)$$

$$x_2 = d_1 \cos(\theta) = \frac{d_1^2 + d_3^2 - d_2^2}{2d_3} \quad (2)$$

$$y_2 = \pm\sqrt{d_1^2 - x_2^2} \quad (3)$$

Where d_1=D(O,R), d_2=D(X,R), d_3=D(O,X).

Because of the two candidates of the resolution, the next step is to find the correct one.

It's obvious that, with the AOAs, the rotational direction of triangle OXR can be determined, CW or ACW, except when the three nodes are almost co-linear with each other. In this case, the next triangle must be select to construct the initial coordinate system. This process continues until a valid triangle is found.

One of the candidates of R has the same rotation direction with that analyzed by AOAs is select. Thus, the placement of X has the effect of fixing a particular rotational orientation, while the placement of R locks in a particular reflective orientation. Now this reflective orientation resembles the reality and only the x-axis has a rotation to the truth.

For the triangle constructing the initial coordinate system, there are six vectors, or edges with direction. We denote the direction in the initial coordinate system with DI_i, and denote the direction of the corresponding vector measured by AOAs with DA_i, where $i = 1,2,\cdots,6$.

We rotate the initial coordinate system with an angle θ, and minimize the following error function:

$$\min E(\theta) = \sum_{i=1}^{6} \left| DI_i - \theta - DA_i \right|^2 \quad (4)$$

Assume that the nodes are random deployed and the six DA_i are independent to each other, then the accuracy of the rotated coordinate system is:

$\sigma = \dfrac{\pi}{4\sqrt{12}\sqrt{6}}$, which is about 5.3 degrees.

C. *Iterative Multilateration*

After the initial coordinate system established, the positions of other nodes are estimated in an iterative way. This process repeats until all the nodes that satisfy the requirements to estimate their position. The process is defined as iterative multilateration which uses multilateration as its main primitive. Besides that, the triangulation and AOA based algorithms also involved.

In this step, we use the ranging information and anchors' locations in a node's neighborhood to estimate its positions. Once a node's position is estimated it becomes an anchor and can assist to estimating other nodes' positions. The process iterates to estimate the locations of as many nodes as possible.

As shown in Figure 4, the algorithm starts by estimating the position of an unknown node which has the maximum number of connections m_i to anchors. When $m_i \geq 3$, the multilateration algorithm is chosen. When $m_i = 2$, the triangulation algorithm described in section B is chosen. And when $m_i = 1$, the AOA based estimation method is adopted. The reason we start from the unknown node with the maximum number of anchors is to obtain better accuracy and faster convergence. This process repeats until the positions of all the nodes that eventually can have at least one anchor are estimated.

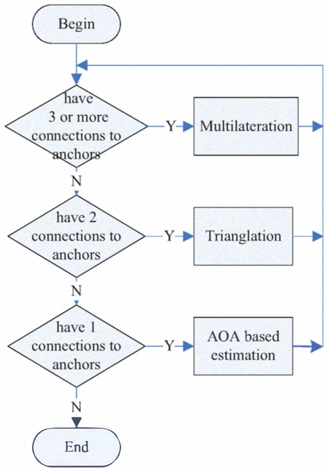

Figure 4. Flow chart of iterative multilateration

A drawback of this step is the error accumulation that results from using of unknown nodes that estimate their positions as anchor, especially to the ones used AOA based estimation method. Fortunately, this error accumulation is not very high because of the high precision of our ranging method and the succeeding optimization step.

D. *mass-spring optimization*

The third step of the algorithm is to run a mass-spring optimization like [18]. Now, we know current position estimate $\hat{p}_i$ of the node n_i, the measured distance $r_{i,j}$ and estimated distance $\hat{d}_{i,j}$ between node n_i and n_j. Let $\hat{v}_{i,j}$ represent the unit vector in the direction from $\hat{p}_i$ to $\hat{p}_j$. The force $\vec{F}_{i,j}$ in the direction $\hat{v}_{i,j}$ is given by $\vec{F}_{i,j} = \hat{v}_{i,j}(\hat{d}_{i,j} - r_{i,j})$. The energy $E_{i,j}$ of nodes n_i and n_j due to the difference in the measured and estimated distances is the square of the magnitude of $\vec{F}_{i,j}$, and the total energy of node i is equal to $E_i = \sum_j E_{i,j} = \sum_j (\hat{d}_{i,j} - \hat{r}_{i,j})^2$. The total energy of the system is given by $E_i = \sum_i E_i$.

The energy E_i of each node n_i reduces when it moves by an infinitesimal amount in the direction of the resultant force $\vec{F}_i$. The exact amount by which each node n_i moves is important for two reasons. First we must ensure that the new position has a smaller energy than the original position; second, we have to ensure that such movement does not result in a local minimum. We can guarantee the first condition by calculating the energy at the new location before moving there to guarantee that the energy reduces. But there is no simple way to guarantee that the move does not result in a local minimum. We empirically selected that each node moves by the amount $\left|\vec{F}_i\right|/(2m_i)$, inversely proportional to the number of neighbors n_i.

E. Coordinate rotation

After the optimization step, the errors of distance between neighbor nodes' are minimized. In order to get a position estimation with higher accurate, the direction the initial coordinate system need adjusting for now we have more edge direction available.

Assume there are L edges in the network, we get 2L vectors. Using the method in like (4), we rotate the initial coordinate system with an angle θ, and minimize the following error function:

$$\min E(\theta) = \sum_{i=1}^{2L} \left|DI_i - \theta - DA_i\right|^2$$

With the same assumption as in section III-B, then the direction accuracy of the resulting coordinate system is:

$$\sigma = \frac{\pi}{4\sqrt{12}\sqrt{2L}},$$

IV. SIMULATION AND CONCLUSION

Our scheme is validated using the prototype node shown in Figure 1. which provides an accuracy of 2 centimeters in ranging and 10 meters in ranging extent.

For financial reasons, the performance of our scheme is evaluated through simulation. The simulation use varying nodes randomly deployed in a 100×80 meters ellipse area. We chose the ranging distance and ranging error according to the performance of the prototype node and use the model of ranging error from -2cm to 2cm in uniform distribution. The goal of the simulation is mainly to compare the AOA assisted multilateration against the pure multilateration algorithm. Only the ratio of the estimated nodes to the total nodes is concerned with varying node density. The density of the nodes was controlled by increasing the node number in the area. For the accuracy of the estimated position have no significant difference between the two algorithms in the condition of the ranging error.

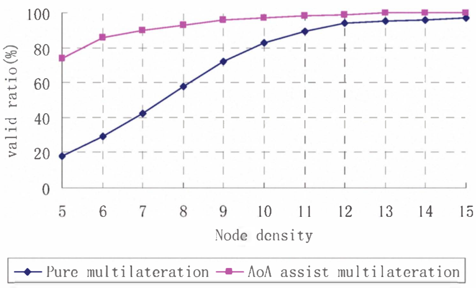

Figure 5. The valid position ratio

From Figure 5 we can draw the conclusion that the AOA based algorithm has significant performance against the pure multilateration. It need about half of the density or about 70% of ranging extend while keep same valid position ratio. It's clear that the ratio has a close relationship to the node density. An economic mean to increase the density is to augment the ranging extend rather than to add nodes into the networks. Investigating a hybrid scheme combined with long distance raging techniques like radio RSSI based methods is our future work.

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