

Topographic Information Based Three-Dimensional Localization Algorithm for Wireless Sensor Networks

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Abstract. There have been a number of three-dimensional localization algorithms designed for wireless sensor networks, and most of them suffer from high computational complexity and error accumulation problems. In this paper, we propose Topographic Information Based Three-Dimensional Localization Algorithm (TIBTDLA) for wireless sensor networks. The basic idea is to reduce error accumulation of three-dimensional localization in wireless sensor networks by referencing topographic information. TIBTDLA exploits a limited region traversal method to locate unknown sensors. Hence, its computational complexity is reasonably low by only traversing the points in the limited region. The proposed method can be implemented in a distributed manner, and this manner gains low time complexity. We compare TIBTDLA with 3D-AML (Three Dimensional Adapted Multi-Lateration). Simulation results show that the TIBTDLA method achieves lower localization error than 3D-AML localization algorithm.

Keywords: Wireless Sensor Networks; three-dimensional; topographic information; localization

1. Introduction

Wireless sensor networks (WSNs) are composed of a large number of sensor nodes deployed in a target area to gather environmental parameters or to detect certain events by using inexpensive microcontrollers. WSNs are self-organizing systems constructed by sensor nodes through wireless communication. Localization is a key technique of WSNs, since in most applications, sensing data without knowing the sensor location is usually meaningless. Only after obtaining the correct locations, it is sensible to monitor the specific location of those events. Therefore, correct localization of nodes is the premise to provide the location information of events [1]. Most localization algorithms in WSNs are based on the assumption that there are a small number of reference nodes (anchors) which locations have been obtained accurately by GPS in advance, and other sensor nodes (unknown nodes) determine their own locations by referencing the anchor nodes through different methods. The current WSNs sensor localization technology can be classified into two categories: range-based and range-free technologies. The range-based algorithms obtain position estimation by measuring the distances to the anchor nodes [2] [3] [4]. Range-free localization algorithms obtain position estimation by using a connectivity matrix of sensor [5].

Most of the previous works on localization focus on two-dimensional terrain and assume that WSNs are deployed in a plane, but three-dimensional localization in WSNs is considerably necessary because WSNs are always deployed in terrains which are often complex three dimensional spaces. Some three-dimensional localization technologies are based on the promotion of two-dimensional technology, such as 3D-AML (Three Dimensional Adapted Multi-Lateration) localization algorithm [6], which is based on 2D-AML localization algorithms.

In a three-dimensional space, given a measured distance from an unknown node to an anchor node, this distance indicates that the unknown node may be located on anywhere of a sphere surface which centers at the

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anchor coordinate with radius of the measured distance. 3D-AML uses three spheres for estimating the location of an unknown node. 3D-AML algorithm can be divided into two phases: intersection and elimination phase and movement phase. In intersection and elimination phase, an unknown node measures the distances to three anchors. The measured distances and the coordinates of three anchors can form three spheres. The surfaces of three spheres intersect at two points. In the movement phase 3D-AML eliminates one of these intersection points with the help of the fourth anchor sphere, and makes the first position estimation with moving the chosen point toward the fourth anchor sphere. Additional anchors' effect can be added on localization to improve accuracy by using the same movement strategy. Like most existing three-dimensional localization methods in WSNs [7] [8] [9], the problems of 3D-AML are the requirement of dense anchors and suffering from high error accumulation, which makes those methods less practical in practical environments.

WSNs may be deployed in mountain terrains, and a quite accurate topographic map of the sensing area can be obtained by the satellite technology progressing [10]. Given a point with coordinate $P(x, y, z)$ in a topographic map, if any two coordinates of x , y , and z are known, then the third one can be obtained by traversing the map. To facilitate discussion, we simply express the relationship of the x , y , and z coordinates of a point in a topographic map as:

$$z = f(x, y) \quad (1)$$

Motivated by the availability of topographic map, this paper proposes Topographic Information Based Three-Dimensional Localization Algorithm (TIBTDLA). TIBTDLA exploits a limited region traversal method to locate unknown sensors in a topographic map. By using topographic map information, TIBTDLA can not only reduce the computation complexity, but also enhance location accuracy. TIBTDLA uses anchors extrapolation technique to locate unknown nodes that are not covered by enough anchors, which makes the algorithm be available for the WSNs containing limited anchors.

The rest of this paper is organized of as follows. Section II describes TIBTDLA localization algorithm in details. Analysis and performance evaluation of TIBTDLA and 3D-AML localization algorithm are given in section III. Finally, section IV concludes the paper.

2. Topographic Information Based Three-Dimensional Wireless Sensor Localization Algorithm

In this section, we describe topographic information based three-dimensional localization algorithm.

2.1 Introduction of algorithm

Given an unknown sensor $P(x, y, z)$ and an anchor $N(x_i, y_i, z_i)$, the distances R_i between the unknown sensor and the anchor can be expressed by (2):

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = R_i^2 \quad (2)$$

From deforming of (2) we can obtain (3):

$$z = z_i \pm \sqrt{R_i^2 - (x - x_i)^2 - (y - y_i)^2} \quad (3)$$

We have introduced that the coordinates of a point in a topographic map can be expressed as $z = f(x, y)$, where x , y and z are x-axis, y-axis and z-axis coordinates of the point, respectively.

In this works, the topographic map information, anchor locations are known and the distances from an unknown node to anchors are measured with errors in advance. Since all nodes must be located in the topographic map, thus the basic idea of our algorithm is to traverse the topographic map and try to find a point which coordinate can satisfy (3) with minimum errors. Then the coordinate of the point is regard as the estimated location of the unknown node.

Give a point (x, y, z) in the topographic map, here $z=f(x,y)$, if (x, y) satisfies (3), then from (3) we can get two answers z' , By constraint of topographic map information, the one which far deviates from z is eliminated. There may be a series of points in the topographic map which can satisfy (3). Our goal is to find the point with minimum difference between z and z' . To achieve this goal, we need more than two anchors and the measured distances to these anchors. We define an optimization method, by which the point in the topographic map with minimum error can be found, and the optimize target is defined as (4):

$$e = \sum_{i=1}^n \xi_i \quad (4)$$

where

$$\begin{aligned} \xi_i &= |z' - z|, \\ z &= f(x, y), \\ z' &= z_i + \sqrt{R_i^2 - (x - x_i)^2 - (y - y_i)^2}, \\ \text{or } z' &= z_i - \sqrt{R_i^2 - (x - x_i)^2 - (y - y_i)^2} \end{aligned}$$

n is the number of anchors and (x_i, y_i, z_i) is the coordinate of anchor i .

The goal of our algorithm is to traverse the points in the topographic map, and find the point which minimizes e in (4). This goal can be achieved by simply traversing all points in the topographic map. A problem arises that it is necessary to traverse all point in the topographic map to find the point?

Given an anchor $N_i(x_i, y_i, z_i)$ with the largest communication distance D , not all points in the topographic map need to be traversed except those inside the circle which is the project of the sphere in xoy plane (the sphere centers at $N_i(x_i, y_i, z_i)$ with radius of D), because only the points inside the area might satisfy (3). Thus to reduce traversal complexity, we adopt a limited region traversal method to find the proper point (Remark 1).

Remark 1: Limited Region Traversal Method

Through limiting the possible region, the search area can be significantly reduced, so it is relatively faster to find the proper point.

The limited region traversal method is based on the largest communication distance D . This concept refers to the maximum distance two nodes can communicate with each other. This topographic map traversal method is based on the xoy plane. We project all nodes into xoy plane. If a sensor can communicate with the anchor, its projection must be inside the projection of the sphere whose center is the anchor, and whose radius is D . This relation is illustrated in Fig. 1.

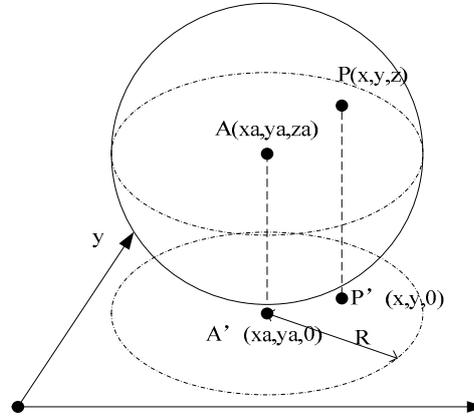


Figure 1. 3-D projection relation of sensors

Here we assume that sensor P can communicate with four anchors. Its projection is bound to the shadow region shown in Fig. 2, which is the overlap region of those sphere projections of four anchors. The overlap region is the bound of traversing range of our algorithm. Through avoiding traversing the whole space, this solution can greatly enhance the traversing speed.

A large WSN may only contain a small number of anchors, and there might be some unknown sensors which are not covered by more than 2 anchors. In this case, the unknown sensors near the anchors can be located at first and then the located sensors are recruited as anchors for localization of other unknown sensors. We term this as anchors extrapolation technique (Remark 2).

Remark 2: Anchors Extrapolation Technique

Suppose we have a group of anchors with known locations which can communicate with unknown sensor P and then use Limited Region Traversal Method to locate P . After localization, add P into the group of known nodes and repeat this process until all sensors are determined.

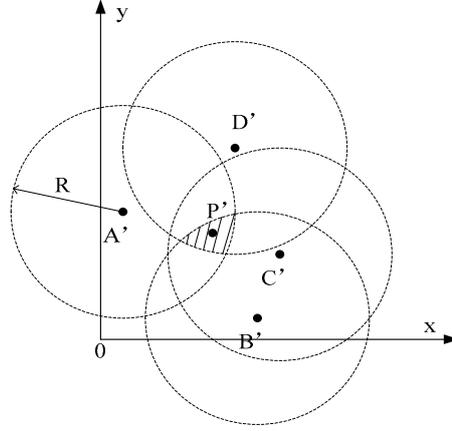


Figure 2. Limited region traversal method

2.2 Steps of algorithm

1) *Information exchange*: The distances from an unknown node to anchors have been measured by TOA [11] and stored by unknown node before this step. At this step, each anchor broadcasts a message, including its own ID, and its own location information. Each of its neighboring sensors receives the message and stores it.

2) *Traversal region limited*: During this period, if an unknown sensor can receive the signal from more than 2 anchors, it will make use of the information obtained from step 1 to generate a series of circles in xoy plane, and the unknown sensor believes its projection falls within the projection of these anchors in the xoy plane. Then unknown sensor calculates the overlap area of these circles, and takes the overlap area as its traversal region.

3) *Location estimation*.

4) *Anchors extrapolation*: After localization, add the located sensor nodes into the group of known nodes and repeat above steps until all nodes are located.

2.3 Implementation procedure

The proposed algorithm is a distributed localization algorithm. Each sensor node uses the information that is locally stored to calculate their own location information.

We suppose there is a sensor node $P(x, y, z)$, who has four neighboring anchors. At the end of step 1, P has stored four neighboring anchors' corresponding locations $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, $D(x_4, y_4, z_4)$ and their measure distances R_1, R_2, R_3, R_4 from every anchor to the node P . From (3), we can obtain (5), (6), (7) and (8):

$$z = z_1 \pm \sqrt{R_1^2 - (x - x_1)^2 - (y - y_1)^2} \quad (5)$$

$$z = z_2 \pm \sqrt{R_2^2 - (x - x_2)^2 - (y - y_2)^2} \quad (6)$$

$$z = z_3 \pm \sqrt{R_3^2 - (x - x_3)^2 - (y - y_3)^2} \quad (7)$$

$$z = z_4 \pm \sqrt{R_4^2 - (x - x_4)^2 - (y - y_4)^2} \quad (8)$$

During step 2, a series of circles can be drawn in xoy plane, whose centers are $A'(x_1, y_1)$, $B'(x_2, y_2)$, $C'(x_3, y_3)$, $D'(x_4, y_4)$, with radiuses D , which is the largest communication distance. Then a grid-scan algorithm [12] will be used to calculate the overlap area. In this algorithm, the whole xoy plane terrain is divided into small grids. Each grid maintains a counter which is initialized to 0. Every time a circle is generated by an anchor,

the counter values associated with the grids within the circle are increased. Once all possible circles are calculated, we scan the whole grid array to find the area with the maximum counter value, and then take this area as the intersection area or traversal region.

At step 3, we choose a grid and suppose its center coordinates is $N(x, y)$. If (x, y) satisfies (5), then from (5) we can get two answers z' . By constraint of topographic map information, the one which far deviates from $z=f(x, y)$ is eliminated. Then we can infer ξ_1 from $\xi_i = |z' - z|$. ξ_2, ξ_3 and ξ_4 can be obtained from (6), (7), and (8) respectively in the same way. Then from (4), we can get the value of e and store it. After traversing all grids in the intersection region, a series of e can be obtained. We choose the minimum value as the optimized e and take corresponding grid's center coordinates (x, y) as the x-coordinate and y-coordinate of node P , the altitude $f(x, y)$ as z-coordinate of node P .

3. Simulations and Analysis

To illustrate the feasibility of this method, we used mat-lab for simulation. The environment we use has dimensions of $1000 \times 1000 \times 1000$. The initial information included a accurate 1000×1000 topographic map, 250 unknown sensors which were randomly deployed in the map, 16 anchors were deployed according to the last sub-graph of Fig. 4, and the largest communication distance is set to $D=300$. Moreover we know distances d_{ij}^* estimated by nodes. The definition of d_{ij}^* is (9):

$$d_{ij}^* = \begin{cases} d_{ij}(1 + A \times k) & \text{if } d_{ij} \leq D \\ -1 & \text{if } d_{ij} > D \end{cases} \quad (9)$$

where d_{ij} refers to the real distance of sensor i and j . A is a random number in range $(-1, 1)$ that refers to different accuracy of distance estimation and k is a parameter. The practical value of k is around 0.005 [11], so we simulated the results under different error conditions from 0.001 to 0.03.

To measure the localization performances, we introduce a metric ‘‘average error distance’’ Ae which is defined as:

$$Ae = \frac{\sum_{i=1}^n \sqrt{(x_i - x_i^*)^2 + (y_i - y_i^*)^2 + (z_i - z_i^*)^2}}{n} \quad (10)$$

In (10), n is the number of all unknown sensors. (x_i, y_i, z_i) and (x_i^*, y_i^*, z_i^*) are real coordinate and estimated coordinate of sensor i , respectively. The better the method performs, the smaller Ae is.

We implement two localization methods, 3D-AML algorithm and TIBTDLA. Both of them use all neighboring anchors of unknown node to locate, and use extrapolation technique to locate unknown nodes that are not covered by more than 3 anchors.

Fig.3 shows two method's performances under different parameters, respectively.

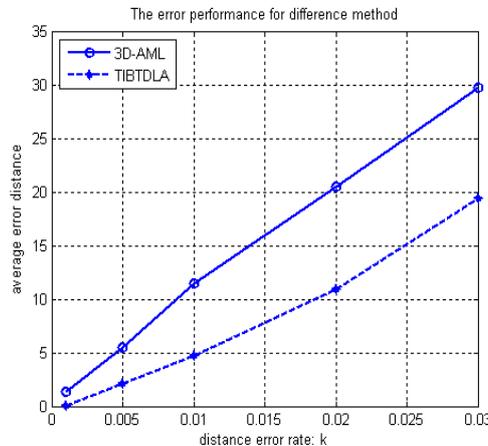


Figure 3. Two method's performances under different parameters

Fig. 3 demonstrates that TIBTDLA always outperforms 3D-AML localization algorithm in terms of average estimation error. That is because TIBTDLA reduces error accumulation by referencing topographic

information. When $k = 0.001$, TIBTDLA can be very precise and the average error distance is only about 0.1-1 meters. With the error range increasing, both average error distance of methods increase, still, TIBTDLA keeps higher location accuracy. For the actual error range (0.005-0.01) of k , TIBTDLA also can get satisfactory results.

Next we show the influence of initial anchors numbers and locations to the localization performance. As illustration in Fig. 4, there are 4, 8, 12 and 16 anchors in four simulations, respectively. In every simulation, there are four same anchors A , B , C and D , which can communicate with each other in a corner. The simulation environment is as following: largest communication distance is set to $D = 300$; total number of sensors is set to 254 (including the original anchors).

The first sub-graph has four anchors; the second has eight anchors; the third has twelve anchors and the last one has sixteen anchors.

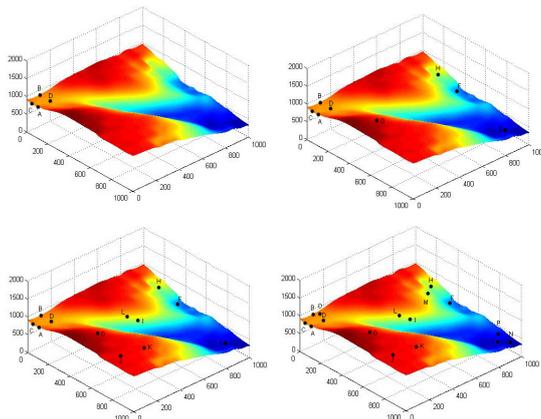


Figure 4. Different initial anchors conditions

Fig. 5 shows performances of TIBTDLA with different anchors numbers and locations respectively.

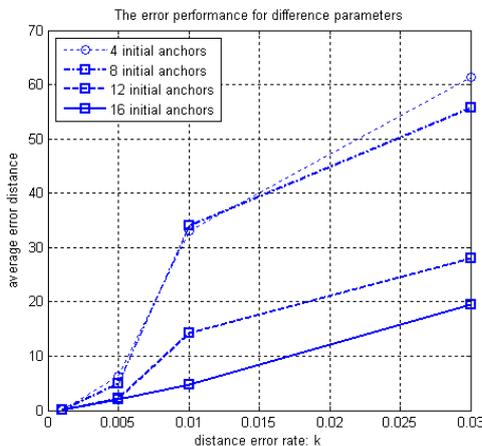


Figure 5. Performances under different anchors numbers

From Fig. 5 we can see that for the actual error range (0.005-0.01) of k , TIBTDLA always can get satisfactory results if there are no less than eight anchors. More anchors contribute less average estimation error. That is because more anchors contribute more precise information, and this can reduce the influence of ranging error for the algorithm. In addition, the more uniformly distributed anchors are the more localization accuracy can be achieved for the algorithm. Therefore, more anchors can make the performance improved obviously.

4. Conclusion

In this paper, we propose TIBTDLA, a localization method that is robust against error accumulation by introducing topographic map. TIBTDLA uses limited region traversal method to locate unknown sensors, which not only reduce the computation complexity, but also enhance location accuracy. TIBTDLA uses

anchors extrapolation technique to locate unknown nodes that are not covered by enough anchors, which makes the algorithm be available for the WSNs containing limited anchors. TIBTDLA is implemented in a distributed manner, and this manner gains low time complexity. Simulation results show that TIBTDLA method has lower localization error than 3D-AML localization algorithm. This algorithm is practical since with the satellite technology progressing, topographic information is very completed in many areas.

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