

A 3D node localization scheme for wireless sensor networks

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Abstract: A 3D node localization scheme for WSNs is developed in this paper. In the scheme, a single mobile beacon submits UWB signals to the sensor nodes to help the whole network localize. Each sensor node receives the UWB signals and adopts TOA technique to measure the distances to the mobile beacon. SDI is proposed as the 3D positioning algorithm executed locally on each sensor node, and simulation is provided to compare it with two representative positioning algorithms, Min-max and Lateration, in terms of some evaluation parameters. The analysis in theory and the simulation show that our scheme can be a utilitarian 3D node localization scheme for WSNs.

Keywords: wireless sensor network, mobile beacon, node localization, space distance intersection, lateration, min-max

Classification: Science and engineering for electronics

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1 Introduction

The node localization problem in wireless sensor networks (WSNs) has received considerable attention in the past, and various schemes have been proposed [1, 2, 3, 4]. Despite of many research proposals on the problem, most of them are designed and evaluated considering only two-dimension (2D) applications where the sensing area is assumed flat and node deployment is assumed dense enough. However, the real sensing area may have a complex terrain and large altitude differences. For example, sensor nodes may be deployed in a mountainous battlefield for surveillance, or be suspended in the air for pollution monitoring. In such applications, it is unreliable to simplify the localization problem to 2D level. However, as three-dimension (3D) node localization is considered, most current schemes are inapplicable any more due to non-uniform node densities, more complex topologies, and obstructions, and so on. The 3D node localization problem in WSNs poses new challenges for the localization scheme design.

Motivated by above observations, in this work, we investigate a 3D node localization scheme for WSNs, which fits the application scenarios where sensor nodes are randomly deployed over 3D terrains. In our scheme, a mobile beacon is used to complete the localization signal coverage and space distance intersection (SDI) method [5] is proposed as the 3D positioning algorithm. Our intention is to provide a utilitarian 3D node localization scheme for WSNs.

2 Proposed scheme

One scenario frequently mentioned in literatures is that sensor nodes are deployed by an aircraft. Our scheme fits well with (but not limited to) this kind of sensor applications. It is presented in terms of two features, one is the beacon's placement strategy, and the other is the 3D position derivation procedure.

2.1 Beacon placement strategy

A mobile beacon placement mechanism [4] is applied in our scheme. A signal submitting device carried by a low-altitude flying aircraft is regarded as the mobile beacon. The mobile beacon is assumed having long-term and unrestricted power supply and can know its own locations by GPS or other doable methods. It hovers above the sensing area and broadcasts localization beacons periodically. Each beacon contains the mobile beacon's current location. The advantage of such a beacon placement mechanism is that it can provide rapid and effective localization signal coverage.

2.2 3D position derivation

The 3D position derivation is handled by each sensor node itself and mainly includes two phases:

Phase 1: Each sensor node measures a set of distances to the mobile beacon, which are necessary for the localization. As for the range method,

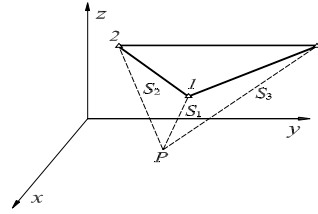


Fig. 1. Determining position using SDI

we assume that the mobile beacon submits UWB signals to the sensor nodes, and these nodes measure the distances relying on Time of Arrival (TOA) technique [6]. Because UWB signal has good multi-path performance and can provide an excellent time resolution, it can complete high-precision ranging by TOA. According to the results of [6], as long as the SNR can be guaranteed (more than 10 dB), even when the distance is long (up to 1 km), the range precision can be kept at dm degree.

Phase 2: Each sensor node derives a 3D position for itself using a certain algorithm, based on the node-beacon distance measurements. SDI is proposed for the purpose, for it has eximious performance in survey engineering field. Moreover, Lateration [1, 2] and Min-max [3] are two representative 2D position derivation algorithms used in WSNs, and they are considered easy to be extended for 3D applications in [7]. For the comparison purpose, SDI, Lateration, and Min-max will all be used as the 3D node positioning algorithm in the latter simulation.

3 Space distance intersection (SDI)

SDI [5] is a flexible, effective and applied technique, usually used in engineering survey for control point densification, and its principle and some characteristics are illustrated in this section.

3.1 Computation formula

As shown in Fig. 1, 1, 2 and 3 are three control points with known coordinates as (x_i, y_i, z_i) ($i=1, 2, 3$). P is the unknown point whose position (x_P, y_P, z_P) is sought. D_{12} , D_{13} , and D_{23} are the distances between every two control points, respectively. S_1 , S_2 , and S_3 are the distance measurements between P and every control point, respectively. P 's positon can be decided using SDI as follows.

At first, let

$$\begin{aligned} X_2 &= x_2 - x_1, Y_2 = y_2 - y_1, H_2 = z_2 - z_1, \\ X_3 &= x_3 - x_1, Y_3 = y_3 - y_1, H_3 = z_3 - z_1, \\ K_1 &= S_1 S_2 S_3 |A|, K_2 = (D_{12}^2 + S_1^2 - S_2^2)/2, K_3 = (D_{13}^2 + S_1^2 - S_3^2)/2, \end{aligned}$$

where $|A| = \sqrt{\sin^2 \varphi_{12} + \sin^2 \varphi_{13} + \sin^2 \varphi_{23} + 2 \cos \varphi_{12} \cos \varphi_{13} \cos \varphi_{23} - 2}$; φ_{12} , φ_{13} , and φ_{23} are included angles between the vectors $\vec{P1}$ and $\vec{P2}$, $\vec{P1}$ and $\vec{P3}$, $\vec{P2}$ and $\vec{P3}$, respectively.

Then, the following equations can be listed:

$$X_P = \frac{1}{\begin{vmatrix} X_2 & Y_2 \\ X_3 & Y_3 \end{vmatrix}} \left(\begin{vmatrix} Y_2 & H_2 \\ Y_3 & H_3 \end{vmatrix} H_P - \begin{vmatrix} Y_2 & K_2 \\ Y_3 & K_3 \end{vmatrix} \right),$$

$$Y_P = \frac{1}{\begin{vmatrix} X_2 & Y_2 \\ X_3 & Y_3 \end{vmatrix}} \left(\begin{vmatrix} H_2 & X_2 \\ H_3 & X_3 \end{vmatrix} H_P - \begin{vmatrix} K_2 & X_2 \\ K_3 & X_3 \end{vmatrix} \right),$$

$$H_P = \frac{K_1 \begin{vmatrix} X_2 & Y_2 \\ X_3 & Y_3 \end{vmatrix} + \begin{vmatrix} Y_2 & H_2 \\ Y_3 & H_3 \end{vmatrix} \begin{vmatrix} Y_2 & K_2 \\ Y_3 & K_3 \end{vmatrix} + \begin{vmatrix} H_2 & X_2 \\ H_3 & X_3 \end{vmatrix} \begin{vmatrix} K_2 & X_2 \\ K_3 & X_3 \end{vmatrix}}{\begin{vmatrix} X_2 & Y_2 \\ X_3 & Y_3 \end{vmatrix}^2 + \begin{vmatrix} Y_2 & H_2 \\ Y_3 & H_3 \end{vmatrix}^2 + \begin{vmatrix} H_2 & X_2 \\ H_3 & X_3 \end{vmatrix}^2}.$$

Finally, P's position is expressed as: $x_P = X_P + x_1$, $y_P = Y_P + y_1$, $z_P = H_P + Z_1$.

3.2 Accuracy assessment

Since the distance measurements contain errors, the computed position of P contains error inevitably. To inspect the relationship between the localization accuracy and the range accuracy, [5] derived the following formulae:

$$\begin{aligned} m_H^2 = & \frac{1}{N}(\sin^2 V_2 + \sin^2 V_3 - 2 \cos \varphi_{23} \sin V_2 \sin V_3) m_{S_1}^2 \\ & + \frac{1}{N}(\sin^2 V_1 + \sin^2 V_3 - 2 \cos \varphi_{13} \sin V_1 \sin V_3) m_{S_2}^2, \\ & + \frac{1}{N}(\sin^2 V_1 + \sin^2 V_2 - 2 \cos \varphi_{12} \sin V_1 \sin V_2) m_{S_3}^2 \end{aligned}$$

$$\begin{aligned} m_V^2 = & \frac{1}{N}(\sin^2 \varphi_{23} + \cos^2 V_2 + \cos^2 V_3 + 2 \cos \varphi_{23} \sin V_2 \sin V_3 - 2) m_{S_1}^2 \\ & + \frac{1}{N}(\sin^2 \varphi_{13} + \cos^2 V_1 + \cos^2 V_3 + 2 \cos \varphi_{13} \sin V_1 \sin V_3 - 2) m_{S_2}^2, \\ & + \frac{1}{N}(\sin^2 \varphi_{12} + \cos^2 V_1 + \cos^2 V_2 + 2 \cos \varphi_{12} \sin V_1 \sin V_2 - 2) m_{S_3}^2 \end{aligned}$$

where m_H and m_V are the horizontal position error standard deviation and the vertical position error standard deviation, respectively; m_{S_1} , m_{S_2} , and m_{S_3} are the range error standard deviation of the three distances, respectively; V_i ($i=1, 2, 3$) are the obliquities of sides $P1$, $P2$, and $P3$ to the plane constructed by the three control points, respectively; $N = |AA^T| = \sin^2 \varphi_{12} + \sin^2 \varphi_{13} + \sin^2 \varphi_{23} + 2 \cos \varphi_{12} \cos \varphi_{13} \cos \varphi_{23} - 2$.

Above formulae demonstrate that the space intersection figure (denoted by φ_{ij} and V_i) determines the influence extent of the range accuracy to the localization accuracy. According to the analysis in [5], while the three control points and the range accuracy are determined (φ_{ij} are determined thereupon), the bigger V_i are, the worse the horizontal position accuracy will be, but the better the vertical position accuracy will be; conversely, smaller V_i are propitious to horizontal positioning, but against to vertical positioning.

4 Simulation

The objective of the simulation is to compare the performance of SDI, Lat-eration, and Min-max under various range error conditions in terms of some evaluation parameters.

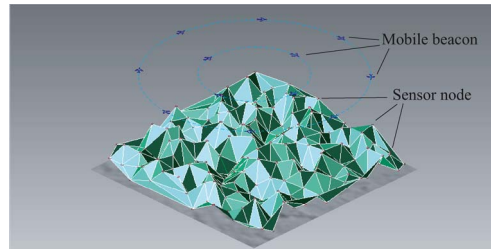


Fig. 2. Simulation scenario

4.1 Simulation scenario

As shown in Fig. 2, 225 nodes are uniformly and randomly deployed in a square sensor field ($100 \text{ units} \times 100 \text{ units}$), and they have random altitude between $0 \sim 20$ units. The mobile beacon is about 50 units higher than the average height of the square area. The beacon fraction is 5%, and hence, the mobile beacon needs submitting about 12 times data packets at different positions during its flight. The mobile beacon's radio range is set to 100 units, and that assures each unknown node in the sensing area can receive at least 8 beacon samples.

The simulation is divided into two phases, ranging and positioning. Matlab is used to perform all the simulation. In the ranging phase, node-beacon distance estimates are obtained by adding some noise to the real distances. The noise conforms to a normal distribution, with zero as the mean and a parameterized percentage of the real distance as the standard deviation. In the positioning phase, while the option is SDI or Min-max, each sensor node selects 3 nearest non-collinear beacon samples for its positioning computation. While the option is Lateration, each unknown node selects 4 nearest non-coplanar beacon samples for the computation.

4.2 Evaluation metrics and parameters

Three metrics are generally considered to evaluate the performances of a node position derivation algorithm:

Accuracy: The distance between a node's real position and computation position, i.e. position error, is used to measure the localization accuracy. Furthermore, the position error is divided into two parts, horizontal position error and vertical position error to investigate an algorithm's performance.

Computation overhead: CPU time is used to measure the computation overhead of a positioning algorithm.

Communication Overhead: In our scheme, each unknown node receives the beacons passively during the localization, and thus, it introduces zero node-to-node communication overhead. Because the three algorithms in comparison are implemented under the same network situations, their communication costs are considered same.

To account for the randomness in generating the distance errors, for every positioning algorithm in comparison, each experiment under a certain range error condition (denoted by a certain standard deviation) is repeated 100 times, and the average position error of all the sensor nodes over 100

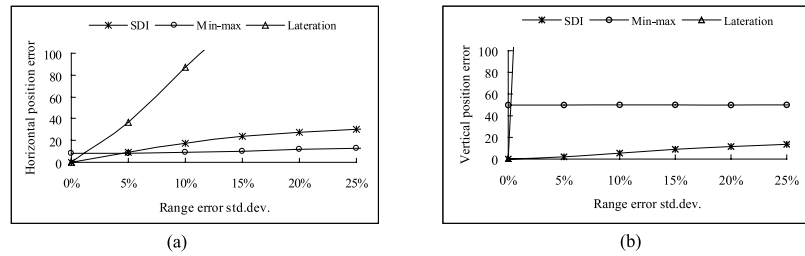


Fig. 3. Position error vs. range error; (a) Horizontal position error vs. range error; (b) Vertical position error vs. range error

times experiments is regarded as the algorithm's localization accuracy under a certain distance error's range. In the same way, CPU time cost of each positioning algorithm under a certain distance error condition is obtained.

4.3 Results and analysis

Fig. 3 (a) and (b) compare the localization accuracy of SDI, Lateration, and Min-max in terms of the horizontal position error and the vertical position error under different range error situations, respectively. From the curves in the figures, Lateration is the worst among them because it performs too sensitive to the range error to obtain acceptable localization accuracy; Min-max is rather insensitive to range error, either at horizontal position or at vertical position; SDI performs also sensitive to the range error, and outperforms Min-max in terms of horizontal position error only when the range is precise (standard deviation $\leq 5\%$), however, it sustains the best vertical position accuracy among the three algorithms under all the range error situations. Moreover, as for SDI itself, it performs better at the vertical positioning than at the horizontal positioning. It can be explained according to the analysis in [5] cited in Section 3. The cause is that in our scheme, the mobile beacon is much higher than the sensor nodes, and hence, most space intersection figures are propitious to the vertical positioning (the average V_i in computation is bigger than 60°).

As for the computation overhead, SDI has almost the same CPU time cost as that of Min-max while Lateration needs the highest CPU time cost among them, about three times more than those of the other two algorithms under the same range error situation.

5 Conclusion

We present a 3D node localization scheme in this paper. In the scheme, the mobile beacon mechanism can provide economical and effective localization signal coverage for the sensor nodes. Since UWB TOA technique is adopted for the ranging, the node-beacon distances can be measured precisely. Moreover, the simulation indicates that our proposed algorithm, SDI, is the optimum for the 3D node positioning compared with Lateration and Min-max while the ranging is precise. Therefore, our scheme can be a utilitarian 3D node localization scheme for WSNs.