3D Localization with a Mobile Beacon in Wireless Sensor Networks

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***Abstract*— Range-free localization schemes could be a good approach to localize sensor nodes from the viewpoint of cost and energy consumption, because range-free schemes require no hardware for measuring distance or angle information. The use of a mobile beacon can improve the localization accuracy and reduce communication overhead between sensor nodes because of the mobility of a mobile beacon. A 3D range-free localization scheme with a mobile beacon proposed by Ou et al. has fine-grained accuracy, scalability, and power efficiency [9]. However, Ou's scheme can have large location errors or cause failure of localization in ill-conditioned cases. To improve the localization accuracy and alleviate the failure of localization, we propose a 3D range-free localization scheme that estimates the location of a sensor node by obtaining two possible points through the intersection of three spheres with centers three reference points and making a decision between the two possible points with another reference point. Simulation results show that the proposed scheme can provide higher localization accuracy compared to Ou's scheme.**

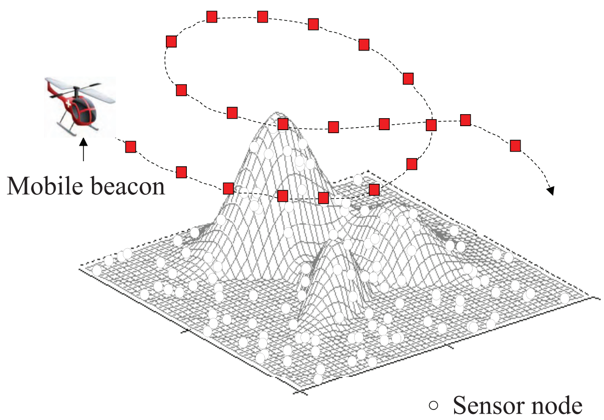

Fig. 1. System environment for the proposed localization scheme.

I. Introduction

In the near future, advances in hardware and radio technology will enable wireless sensor networks capable of sensing, data processing and wireless communication. A collection of sensor nodes which have limited sensing region, processing power, and energy is randomly deployed and connected through networking in order to monitor a wide area. The wireless sensor networks can be used in many promising applications such as battlefield surveillance, real-time monitoring seismic waves, machine operation, bush fire monitoring, emerging diseases control, vehicle tracking, and traffic control [1].

Localization schemes are usually divided into range-based and range-free schemes. Range-based schemes [2]-[4] localize a sensor node with the measured distance or angle information, while range-free schemes estimate the location of a sensor node without the measured information. Since range-free schemes need no additional devices for measuring which are expensive and energy-consuming, range-free schemes are more promising in wireless sensor networks composed of a lot of tiny and cheap sensor nodes having limited energy. Static beacons or mobile beacons are used for localization. The use of a mobile beacon has the same effect as using many static beacons. For the reason, the use of a mobile beacon can improve the localization accuracy more than the use of static beacons.

Several 2D range-free localization scheme with a mobile beacon had been proposed [5]-[8]. If we consider the cases that sensor nodes are deployed in 3D environments like mountains, a 3D localization scheme is more promising than a 2D localization. A 3D range-free localization scheme with a mobile beacon was proposed by Ou et al. [9]. In Ou's scheme, the location of a sensor node is estimated based on the geometric corollary, which states that a perpendicular line passing through the center of a sphere's circular cross section also passes through the center of that sphere. Ou's scheme is accurate, distributed, scalable and power efficient. However, in Ou's scheme, a small error in beacon(reference) points can make large location error; the location error may be close to infinity. In addition, if a mobile beacon moves on the same plane in 3D (e.g., moves at the fixed height), all beacon points are also located on one plane, resulting in the failure of localization. To improve the localization accuracy and alleviate the failure of localization, we propose a 3D localization scheme that estimates the location of a sensor node by obtaining two possible points through the intersection of three spheres with centers three beacon points and making a decision between the two possible points with another beacon point. Simulation results show that the proposed scheme outperforms Ou's scheme in the localization accuracy.

The remainder of this paper is organized as follows. In

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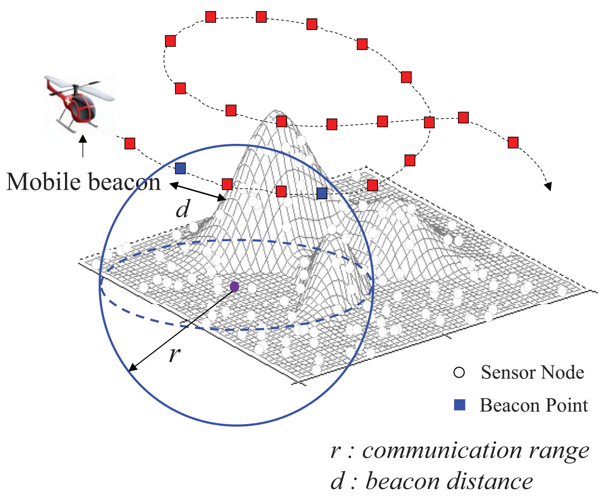

Fig. 2. Selection of beacon points among the received locations from a mobile beacon.

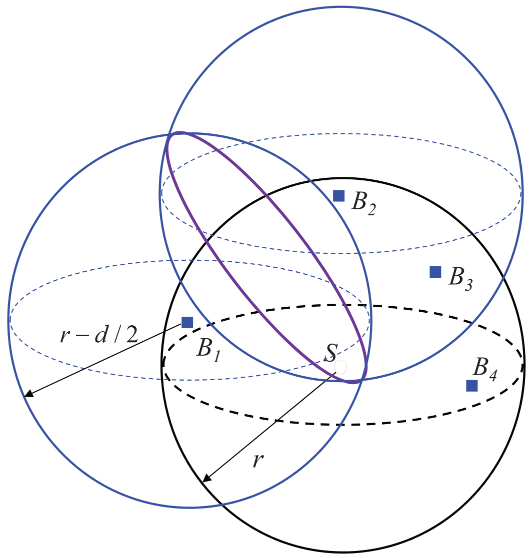

Fig. 3. Intersection circle of the two spheres with centers B_1 and B_2.

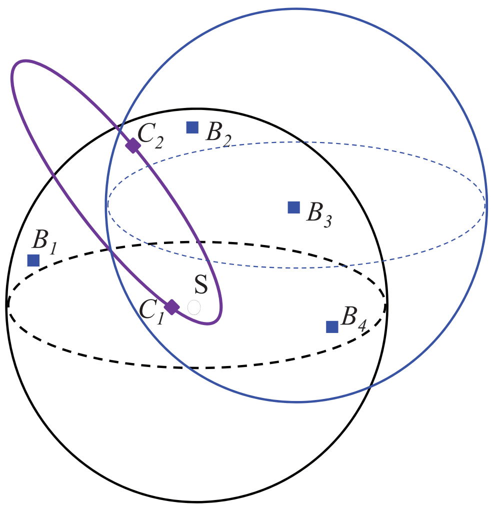

Fig. 4. Intersection of the intersection circle and the sphere with center B_3.

section II, a range-free localization scheme with a mobile beacon is proposed. Section III evaluates the localization accuracy of the proposed scheme, compared to Ou's scheme. Finally, this paper is concluded in section IV.

II. Proposed Localization Scheme

In this section, we explain in detail how to localize sensor nodes with a mobile beacon. First, we describe system environment for the proposed localization scheme. Then, we explain the method of the location estimation in the proposed localization scheme.

A. System Environment

A mobile beacon is assumed to know its own location with a module like a GPS receiver. A mobile beacon moves through the sensing space and periodically broadcasts a beacon message including its current location as shown in Fig. 1. A mobile beacon is assumed to have sufficient energy for moving and broadcasting beacon messages.

Sensor nodes that are deployed in 3D environments transmit no data to a mobile beacon and just receive the beacon messages from the mobile beacon.

B. Location Estimation

Let us assume that the communication range for sensor nodes and a mobile beacon is r. The distance between a series of two received locations from a mobile beacon is called beacon distance. Let us denote the beacon distance by d. As shown in Fig. 2, when a mobile beacon is within the communication range from a sensor node, the sensor node can receive the beacon messages including the location of the mobile beacon. Among the received locations, the first and last locations are selected as beacon points. The beacon points are not located exactly on the communication sphere because of the beacon distance. When we consider the beacon distance, the distance between a beacon point and a sensor node has a range between r and $r-d$, so the distance between them can be estimated as the middle value, $r-d/2$. After a sensor node obtains four beacon points, the sensor node can estimate its own location using the beacon points.

The problem of the location estimation of a sensor node can be described as follows:

$$\begin{cases} \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} = r-d/2 \\ \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} = r-d/2 \\ \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} = r-d/2 \\ \sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2} = r-d/2 \end{cases}, \quad (1)$$

where (x, y) is the location of a sensor node S and (x_i, y_i) is the location of the i^{th} beacon point B_i.

The location of a sensor node can be estimated by solving the equations in (1). As shown in Fig. 3, the points on the intersection circle of the two spheres with centers B_1 and B_2 are the solutions of the first and second equations in (1). Then, as shown in Fig. 4, the two intersection points C_1 and C_2 of the intersection circle and the sphere with center B_3 are the solutions of the first, second, and third equations in (1). One of the two intersection points C_1 and C_2 is closer to the sphere with center B_4 than the other intersection point. If the following inequality is satisfied, C_1 is estimated as the location of the sensor node S; otherwise, C_2 is estimated as the location of the sensor node.

$$|\|B_4 - C_1\| - (r - d/2)| < |\|B_4 - C_2\| - (r - d/2)| \quad (2)$$

It is noteworthy that the maximum location error does not exceed two times the communication range because the location of a sensor node is estimated based on the intersection of three spheres. The proposed scheme provides the upper bound of location error, while Ou's scheme may cause location error close to infinity.

III. Performance Evaluation

In this section, we explain how to set up the parameters for simulations and compare the proposed scheme and Ou's scheme in the sense of the localization accuracy through simulations.

A. Simulation Setup

The sensing space is a rectangular parallelepiped of 100 x 100 x 100 m^3. Sensor nodes are deployed uniformly at random; the number of the sensor nodes is 100. A mobile beacon is assumed to move at a velocity of 1 m/s and broadcasts a beacon every beacon interval 1 sec. Without loss of generosity, a mobile beacon is assumed to move in a straight line. The communication range for a mobile beacon and sensor nodes is 20 m. We use the Matlab as a simulator.

To improve the reality of our simulations, irregularities of the communication range can be modeled as $\hat{r} = r + e_r$, where e_r is the independent and identical random value with the Gaussian distribution $N(0, \sigma_r^2)$.

B. Simulation Results

In this section, we show the localization accuracy according to the beacon distance and the communication range. In addition, we show that the proposed scheme outperforms Ou's scheme in the localization accuracy under irregularities of communication range.

Fig. 5 shows the average location error as a function of the beacon distance. In the proposed scheme, the average location error increases as the beacon distance increases, because the increase of the beacon distance causes the increase of the estimation error in the distance between a sensor node and a beacon point. In contrast to the proposed scheme, Ou's scheme can cause the unacceptably large location error. Fig. 6 shows the average location error as a function of the communication range. In the proposed scheme, the average location error increases as the communication range increases. Through Fig. 5 and Fig. 6, the beacon distance and the communication range have to decrease in order to improve the localization accuracy.

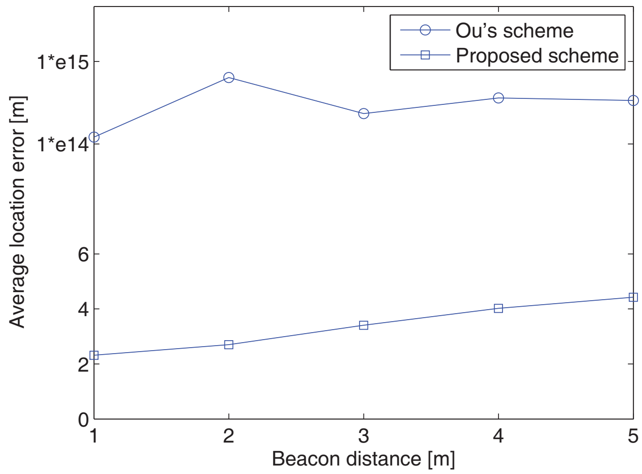

Fig. 5. Average location error according to the beacon distance.

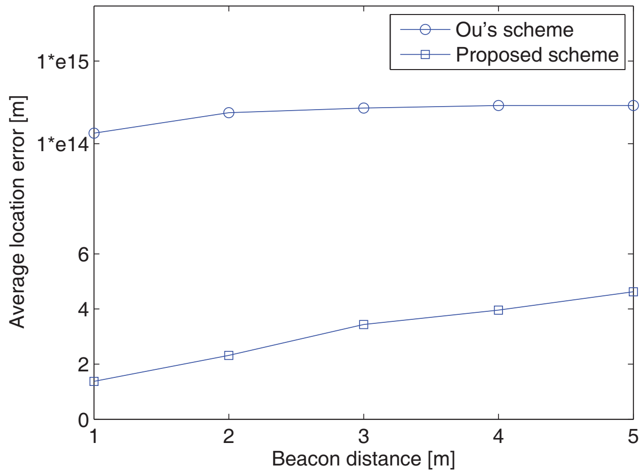

Fig. 6. Average location error according to the communication range.

As shown in the average location error of Ou's scheme in Fig. 5 and Fig. 6, a small number of very large location errors can severely affect the average location error, so the distribution of location errors can be used as an alternative metric to evaluate the localization accuracy. Fig. 7 shows the cumulative percentage of sensor nodes according to location error. The distribution of location errors shows that the proposed scheme outperforms Ou's scheme.

Fig. 8 shows the percentage of sensor nodes with location error below 10m according to the standard deviation in irregularities of the communication range. As irregularities of the communication range increase, the gap in the percentage of sensor nodes between the proposed scheme and Ou's scheme increases. Fig. 8 verifies that the proposed scheme is more robust to irregularities of the communication range than Ou's scheme.

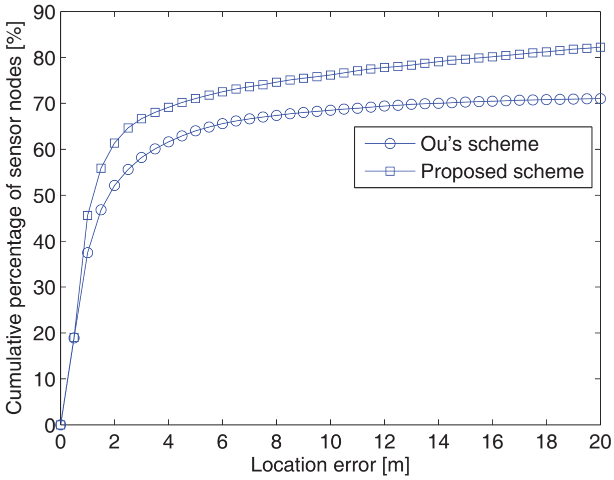

Fig. 7. Cumulative percentage of sensor nodes according to location error.

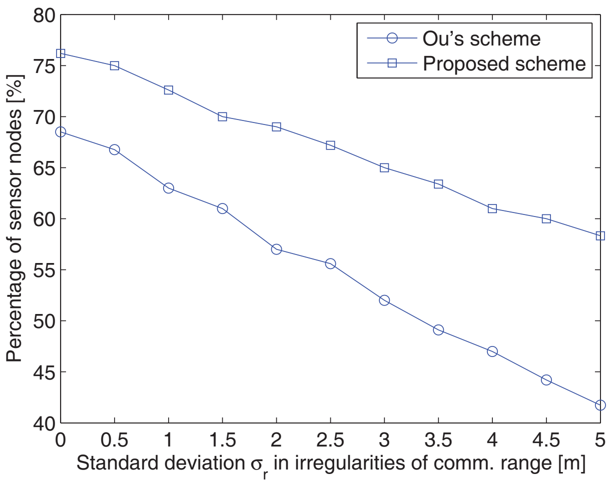

Fig. 8. Ratio of sensor nodes with location error below 10m according to irregularities in communication range.

IV. Conclusion

In this paper, we proposed a range-free localization with a mobile beacon based on the intersection of three spheres with three beacon points and the decision with another beacon point. Simulation results show that the proposed scheme outperforms Ou's scheme in the localization accuracy. In addition, simulation results show that the proposed scheme is more promising than Ou's scheme for real environments where there exist irregularities of the communication range. The further work is to find an appropriate path of a mobile beacon for the proposed scheme because the path of the mobile beacon affects the deployment of beacon points resulting in the localization accuracy [10], [11].

Acknowledgment

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