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Planning the obstacle-avoidance trajectory of mobile anchor in 3D sensor networks

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Abstract Localization plays an important role in many applications of wireless sensor networks. Recently, mobile anchor assisted localization methods become promising, and the moving trajectory planning of anchor is an interesting and basic issue in these methods. In this paper, an obstacle-avoidance trajectory planning method for three-dimensional wireless sensor networks is proposed. After dividing the network into grids, a depth-first-search algorithm with greedy strategy is proposed to get the approximately shortest path, and a trigonal function based localization method is presented to estimate the positions of the sensor nodes. Simulations show that this method can obtain almost the optimal path and localize almost all the sensor nodes.

Keywords wireless sensor networks, three-dimension, localization, mobile anchor, path planning

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1 Introduction

Recently, wireless sensor networks have been widely used in object tracking [1], environment monitoring [2], and so on. Location of sensed data is one of the most concerned information in many applications of wireless sensor networks, and it also supports a number of fundamental network services, such as network routing, topology, coverage control, as well as boundary detection. Thus, self-localization capability is a highly desirable characteristic of wireless sensor networks.

The position of each sensor can be determined by a manual deployment, but it becomes tedious and error-prone to the large-scale sensor networks. If each sensor node is equipped with a global positioning system (GPS) receiver, the problem can be solved. But GPS device is costly in terms of power, volume and money. To estimate the geographic position of each sensor node, many self-localization algorithms are proposed, and most of them are anchor-based [3]. Anchor is a special sensor node which has a priori knowledge of its own position with respect to some global coordinate system. During localization, the

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ordinary sensor nodes measure their distances or angles to the anchors. Generally, anchors are equipped with GPS receivers and always awake during localization, which makes them more expensive and consumes higher energy than ordinary nodes. In this paper, we focus on static sensor networks, where the sensor nodes do not move after deployment. In this case, the anchors become useless after localization.

To eliminate the aforementioned drawbacks of existing anchor-based localization algorithms, mobile anchor assisted methods become promising. In these methods, one or several anchors traverse the sensor network along some trajectory, and broadcast packets including its real-time coordination periodically. Meanwhile, the ordinary sensor nodes measure the geographic information to mobile anchor to estimate their locations. Obviously, how to plan the mobile trajectory of anchor is very important when mobile anchor assisted method is adopted.

Nowadays, wireless sensor networks have been applied in three-dimensional (3D) regions such as aerospace and underwater, where the moving trajectory of the mobile anchor should avoid colliding with the obstacles in the deployment region. However, the existing path planning methods are always based on the assumption of a flat and unobstructed deployment area, which are not suitable for 3D obstructed scenarios.

In this paper, we propose an obstacle-avoidance trajectory planning method for 3D sensor networks. The 3D region considered in this paper is defined as the outer space or underwater environment, where the anchor can move freely in any direction. The main contributions of this paper are summarized as follows. (1) An obstacle-avoidance trajectory planning method is proposed, which can be applied to 3D obstructed deployed areas; (2) a localization method based on trigonal function is proposed to decrease the computation complexity.

The rest of this paper is organized as follows. The related work is introduced in Section 2. In Section 3, the obstacle-avoidance path planning method is proposed, whose performance evaluation is conducted in Section 4. Finally, the conclusion is drawn in Section 5.

2 Related work

The mobile anchor assisted localization methods consist of two important issues: localization schemes of ordinary sensor nodes and the trajectory planning of mobile anchor.

2.1 Localization algorithms

Here, the localization algorithm only refers to the estimation method of the ordinary sensor nodes position. In mobile anchor assisted localization methods, the sensor nodes can measure the distance to the mobile anchor using received signal strength (RSS), time of arrival (ToA), or time difference of arrival (TDoA), and then their positions can be estimated.

The method proposed in [4] required the mobile anchor to traverse straight through the communication range of a sensor node. The sensor node chooses the first beacon moving into the nodes range and the beacon with the largest RSS as two reference points. In particular, the proposed method obtained a geometric formula about angles between sensor node and reference points, and then determined the nodes position with the help of distance information measured by RSS. The geometrical localization algorithm was also utilized in [5], but it utilized trilinear coordinates in two-dimensional (2D) and volume based approach in 3D, which achieved an accurate estimation based on ToA measurements without time synchronization. Moreover, two attractive movement strategies for mobile anchor were presented in [5]. For the sparse networks and networks with irregular topology, Zhou et al. [6] proposed a localization method based on the use of a mobile anchor and a map registration algorithm.

Besides the above deterministic methods, the probabilistic localization methods such as Bayesian inference [7], and parametric or non-parametric probabilistic estimation techniques [8] have been demonstrated more accurate than other methods, but they require an initial calibration phase before network deployment.

The above range-based localization methods consume a considerable amount of energy while ranging, so range-free localization approaches become cost-effective alternatives to range-based approaches. The (weighted) centroid algorithm is an energy-efficient approach but its localization precision is low. To overcome this problem, Xiao et al. [9] proposed the arrival and departure overlap approach using a single mobile anchor. This method used the arrival and departure information of the walking beacon to improve the localization precision of centroid method. Because the trajectory of the mobile anchor is a straight line during a small period, we can obtain some intersected lines across the sensor nodes and utilize the intersection point of these lines as the estimation of the sensors position. For instance, the perpendicular intersection method utilizes the geometric relationship of a perpendicular intersection to compute node positions, on the basis of contrasting the RSS from the mobile beacon to a sensor node [10]. Another method using the geometry conjecture of perpendicular bisector of a chord was presented in [11]. Different from the above methods, two mobile anchor assisted probabilistic approaches were proposed in [12], which used a particle filter (also called sequential Monte Carlo method) to perform a Bayesian filter on a sample representation.

The above methods utilize a single mobile anchor with omni-directional and single-power-level antenna. Some approaches break this limit and utilize different kinds of mobile anchors. A multi-power-level mobile anchor was used in the method proposed in [13] where the node localization problem was formulated as a convex optimization. This formulation can effectively solve the problem when infeasible beacons occur because of the effects of radio irregularity and obstacles. The approach proposed by [14] utilizes mobile anchor nodes fitted with four-directional antennas, and the sensor nodes apply the statistical median to compute their coordinates. Rectangle overlapping approach [15] uses a mobile anchor with a rotatable antenna to provide sensor nodes with rotation angle and position to localize. The method proposed in [16] uses three mobile anchors that form a regular triangle, and the sensor node estimates its location using centroid method.

Nowadays, wireless sensor networks have been increasingly applied in 3D terrains, and some special localization methods for 3D networks have been proposed [17]. A multidimensional-scaling-based 3D localization method was proposed in [18], but it is very complicated. We proposed a mobile anchor assisted localization algorithm in 3D sensor networks in [19], but it needs four mobile anchors. In [20], a method similar to the one in [11] was proposed where each sensor node estimates its own location by applying basic geometry principles.

2.2 Trajectory planning algorithms

As mentioned above, the moving trajectory is a basic problem for mobile anchor assisted localization method. The trajectory should satisfy the following properties.

- It should pass closely to as many potential node positions as possible, aiming to localize as many unknown nodes as possible [7].
- It should provide each unknown node with at least three (four) non-collinear (non-coplanar) referencing positions in 2D (3D) region to achieve a unique estimation of nodes position [7].
- It should be as short as possible to save the energy of the mobile anchor and the time of localization [21].

Random moving trajectories, including random waypoint, Gauss-Markov trajectory, and random direction mobility model, are commonly used in some localization methods. However, these trajectories cannot cover the entire network and fail to localize all sensor nodes. To overcome this drawback, three determined trajectories including scan, double-scan and Hilbert are proposed in [22]. Scan and double-scan are composed of a series of straight lines, and Hilbert is Hilbert spacing-filling curve. Although these determined trajectories outperform random trajectories, they may introduce collinear packets leading to ambiguity of location estimation. Aiming to overcome this drawback, Circles and S-curves were proposed in [23], but they cannot traverse the whole region. Based on the optimal distribution of positions where the mobile anchor broadcasts packets, K-coverage trajectory was proposed in [24]. The trajectory can be further shortened using clustering technology [25].

According to the topology of the sensor network, the moving trajectory can be designed dynamically. Based on the feedback information of ordinary sensor nodes to mobile anchor using directional antenna, a novel heuristic dynamic planning method was proposed in [26]. In [21], a virtual force trajectory was presented for the non-uniformly deployed sensor networks.

Generally, the deployment areas contain many obstacles which the mobile anchor must avoid. In [13], the boundary nodes around the obstacle have been discovered by some boundary recognition algorithms, so the anchor can avoid the obstacles when it moves besides these boundary nodes. It imposes additional energy consumption on localization algorithm. In [10], the anchor is equipped with a rotating arm to bypass an obstacle, which may not be applicable for the other environments. We have proposed an obstacle-avoidance trajectory planning method based on Max-Min ant system in [27], which has high-complexity for 3D regions. Moreover, these methods are designed for 2D regions. In this paper, a greedy-strategy-based depth-first-search algorithm and 3D-Hilbert curve are provided to plan the obstacle-avoidance trajectory in 3D sensor networks. Although the obstacle-avoidance path planning has been studied in robotics, the goal is different: In robotics, the robot needs to travel over *all* points in the obstacle-free region, while it only needs travel a part of obstacle-free region to ensure that each unknown node can receive the messages from mobile anchor in localization of sensor network.

3 Trajectory planning method

The proposed method is based on the following assumptions:

- The mobile anchor can be modeled as a point while the size of anchor is not considered.
- The obstacles in the deployed region are stationary, which enables us to design the trajectory off-line.
- None of the obstacles divide the region into disjoint parts.

Let $\boldsymbol{W}$ be the deployment region of sensor network, Algorithm 1 presents the main procedure of obstacle-avoidance trajectory planning algorithm.

Algorithm 1 Obstacle-avoidance trajectory planning

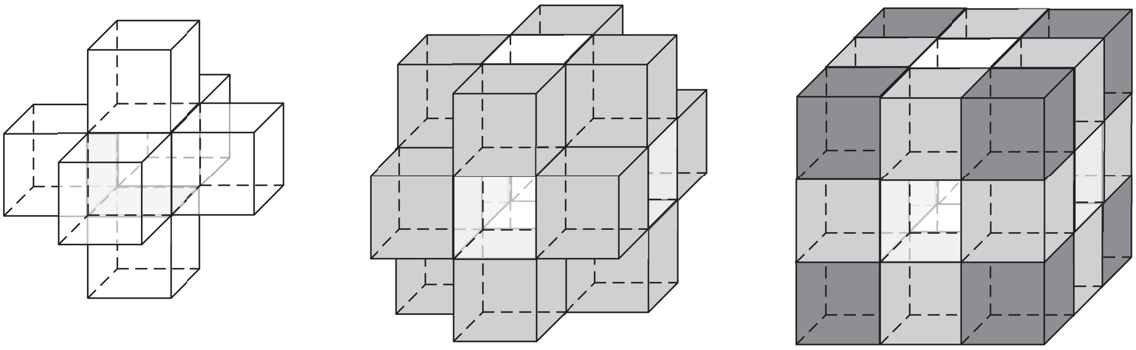
```
Require: $\boldsymbol{W}$ is the circumscribed cube of the deployment region of sensor network;
  Decomposing $\boldsymbol{W}$ into cubes;
  Mapping $\boldsymbol{W}$ to a graph $\mathbf{G}$;
  Obtaining trajectory $\boldsymbol{P}$ visiting free cubes;
  repeat
    Moving along Hilbert in a free cube;
    Moving to next cell $c$ along $\boldsymbol{P}$;
    while $c$ is localized do
      $c \Leftarrow$ the parent cube of $c$ on $\boldsymbol{P}$;
    end while
  until all the empty cubes are localized
```

Firstly, the deployment area is divided into cubes of the same size and the relationship between each cube and obstacle is judged. This relationship is divided into three kinds:

- *Free.* If a cube departs from all obstacles, it is called a free cube.
- *Mixed.* If a cube is intersected with one or more obstacles, it is called a mixed cube.
- *Full.* If a cube is occupied by obstacles, it is called a full cube.

Suppose the mobile anchor only visits the free cubes. We can map the relationship between free cubes to a graph $G = (V, E)$, where V is the set of vertices and E is the set of edges. Each $v \in V$ corresponds to a free cube, and $(u, v) \in E$ if, and only if, the corresponding free cubes are adjacent. Note that there are three criteria to judge whether two cubes are adjacent: (1) they have a common plane; (2) they have a common edge; (3) they have a common vertex. Figure 1 shows the above cases.

After decomposing the deployment area, we can design the trajectory. We call the trajectory visiting among free cubes as *global trajectory*, and the trajectory visiting within each free cube as *local trajectory*. Then, the detail of each step of Algorithm 1 is presented as follows.



(a) (b) (c)

Figure 1 Adjacent cubes. (a) Common plane; (b) common edge; (c) common vertex.

3.1 Planning global trajectory

Since the deployment area is translated into a graph, this problem is similar with traveling salesman problem (TSP), which determines the shortest closed tour that visits each vertex exactly once. TSP is one of the classic non-deterministic polynomial-time hard combinatorial optimization problems, and many algorithms are proposed to solve this problem, such as ant colony system [28]. These methods always assume the graph is a Hamilton graph, which contains a solution at least; however, the graph G may not meet this assumption. Hence, we present a simple algorithm to obtain the trajectory visiting all free cubes.

As shown in Algorithm 2, this method is based on the depth first search of graph.

If G is a non-Hamilton graph, the global trajectory will contain many backtracks, which lengthen the trajectory. In order to decrease backtracks, we combine the depth first search with greedy strategy.

In Algorithm 2, the first vertex u to be visited satisfies

$$u = \operatorname{argmin}\{\text{degree}(w) \mid w \in V\}, \tag{1}$$

where degree(w) is the degree of w.

Suppose the current visiting vertex is v, the next vertex u to be visited is

$$u = \operatorname{argmin}\{\text{degree}(w) \mid w \in S_v\}, \tag{2}$$

where

$$S_v = \{w \mid (w, v) \in E \wedge \text{visit}(w) = false\} \tag{3}$$

is the set of vertices adjacent to v and un-visited until now.

If $S_v = \Phi$, we need backtrack to the nearest parent vertex u along the trajectory where visit(u) $= false$, and u is a parent vertex along the trajectory nearest to v, i.e., if $(u, u_1, u_2, \ldots, u_k, v)$ is the trajectory, and $S_{ui} = \Phi (i = 1, 2, \ldots, k), S_u \neq \Phi$, then u is the next vertex to be visited.

After a vertex v is visited, set visit(v) $= true$, and decrease the degree of its adjacent vertices by 1, i.e.,

$$\text{degree}(u) = \text{degree}(u) - 1 \ \textit{if} \ (u, v) \in E. \tag{4}$$

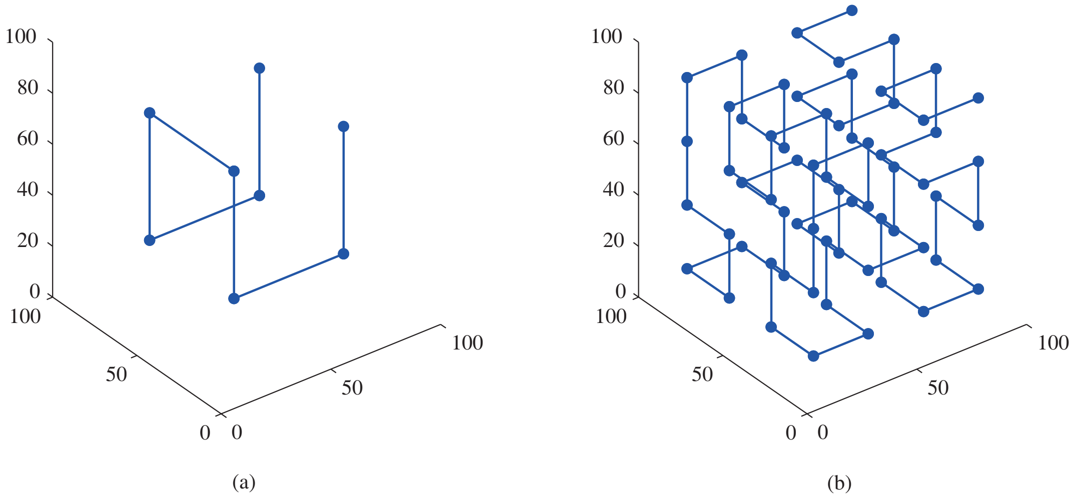
In Algorithm 2, the first *for* loop initialize the arrays, and select the first vertex to be visited according to (1). The second *for* loop decrease the degrees of adjacent vertices of the first visited vertex. The *while* loop plans the global trajectory according to (2) and (3). Algorithm 2 outputs a vector $\boldsymbol{P}$ as the global trajectory.

3.2 Planning local trajectory

We have studied some common 3D trajectories in [29], and found that 3D Hilbert curve (shown in Figure 2) outperforms the other trajectories. Therefore, we utilize 3D Hilbert curve as the local trajectory.

Algorithm 2 Planning trajectory visiting free cubes

```
Require: $G = (V, E)$, $n = |V|$;
  for $i = 1$ to $n$ do
    visit($i$) $\Leftarrow$ false;
    $parent(i) \Leftarrow 0$;
    $degree(i) \Leftarrow$ degree of $V(i)$;
  end for
  $curr \Leftarrow argmin\{degree(i)|v(i) \in V\}$;
  visit($curr$) $\Leftarrow$ true;
  $VisitedNum \Leftarrow 1$;
  $P \Leftarrow \Phi$;
  for $i = 1$ to $n$ do
    if $(v(i), v(curr)) \in E$ then
      $degree(i) \Leftarrow degree(i) - 1$;
    end if
  end for
  while $VisitedNum < n$ do
    $S \Leftarrow \{v(j)|(v(curr), v(j)) \in E \wedge$ visit($j$) =false$\}$;
    if $S \neq \Phi$ then
      $k \Leftarrow argmin\{degree(i)|v(i) \in S\}$;
      $P \Leftarrow P \cup \{(v(curr), v(k))\}$;
      $parent(k) \Leftarrow curr$;
      $VisitedNum \Leftarrow VisitedNum + 1$;
      visit($k$) $\Leftarrow$ true;
      $curr \Leftarrow k$;
      for $i = 1$ to $n$ do
        if $(v(i), v(curr)) \in E$ and visit($i$)=false then
          $degree(i) \Leftarrow degree(i) - 1$;
        end if
      end for
    else
      $P \Leftarrow P \cup \{v(curr), v(parent(curr))\}$;
      $curr \Leftarrow parent(curr)$;
    end if
  end while
```



(a) (b)

Figure 2 (Color online) 3D Hilbert curve. (a) One-order Hilbert curve; (b) two-order Hilbert curve.

Using this trajectory, a sensor node can receive many packets from the mobile anchor, and it must be able to receive three successive packets if the parameters of Hilbert curve are adopted [29]. As illustrated in Figure 3, let U be an ordinary node, and suppose it receives three packets ordered by i, j and l. Based

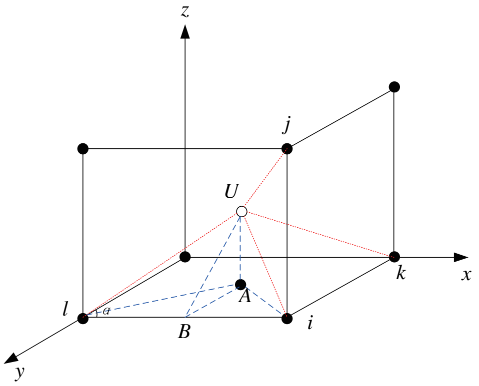


Figure 3 (Color online) Calculate the x coordinate of U.

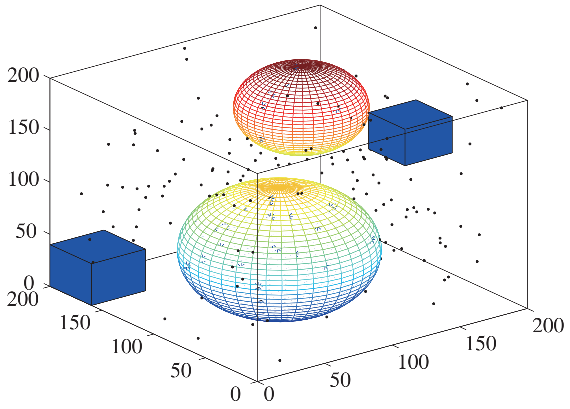


Figure 4 (Color online) 3D simulation environment.

on cosine theorem,

$$\cos(\alpha) = \frac{d_{ul}^2 + s^2 - d_{ui}^2}{2 \times s \times d_{ul}}, \tag{5}$$

where d_{ul} and d_{ui} are the distances between U and l, i respectively, and s is the side length of the cube to decompose the region. Hence, the estimated x coordinate of U is

$$x_U = x_A = x_B = x_l + d_{ul} \times \cos(\alpha). \tag{6}$$

Note that x_l can be deduced by the order of the Hilbert curve, so x_U can be calculated using the above equation. Similarly, the other coordinates, y_U and z_U, can also be obtained.

This position estimation consumes 21 multiplies (divisions) and 9 additions (subtractions), and it only utilizes 3 messages of mobile anchor for each unknown node. The time complexity is lower than the other methods. As comparisons, the time complexity of the proposed method in [18] is $O(kM^3)$, where all received messages from mobile anchor are divided into k sets of M messages, so it becomes more complex with more messages.

4 Performance evaluation

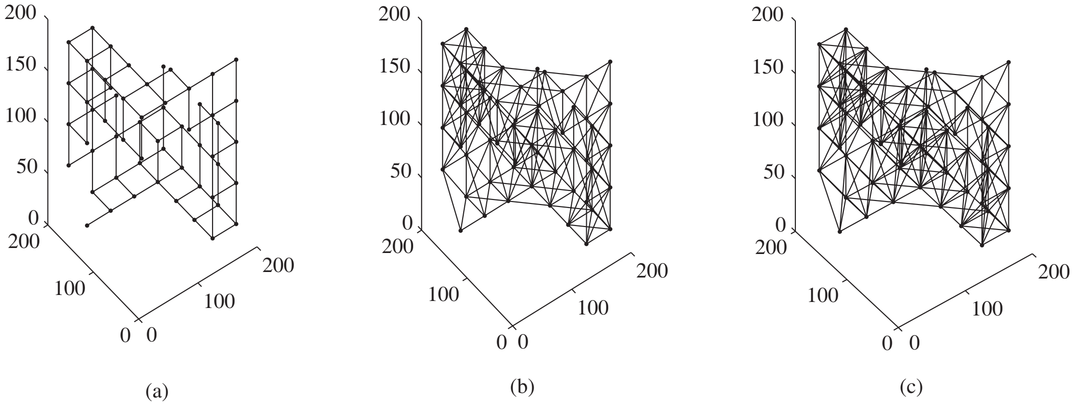
4.1 Experiment setup

We evaluate the performance of our proposed method using Matlab 7.0. The deployment area is shown in Figure 4, which is a cube of side length 200 m, containing two cubic and two circular obstacles (the shadowed part in Figure 4). There are 200 sensor nodes uniformly deployed in this region at random (the dots in Figure 4).

Four different sizes of the cube are utilized to decompose the region, which are 20, 25, 40, and 50 m. Moreover, we evaluate the performance of the three different criteria, mentioned in Section 3, to judge whether two cubes are adjacent.

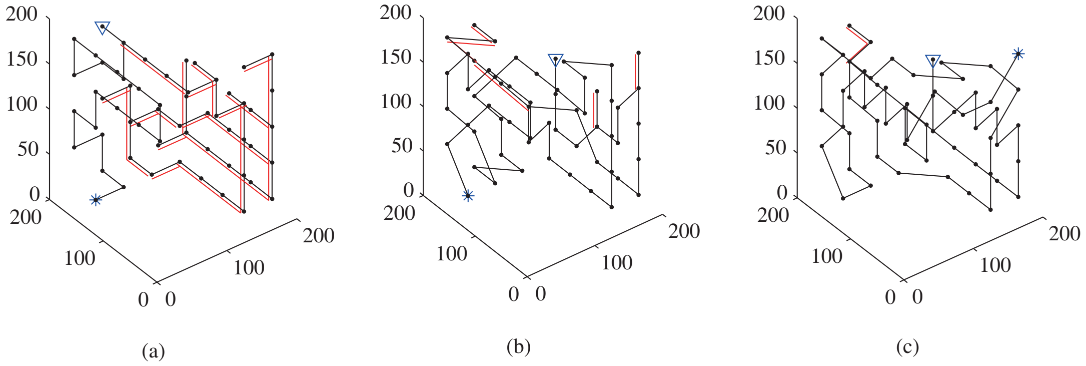
The radio range of the mobile anchor is set to 10, 20, 30, 40 and 50 m respectively. In order to make the experiment conform to real applications, we also set the ranging error to be 10%.

The evaluation criteria include the path length, number of localizable sensor nodes, and localization accuracy. Because the length of local trajectory is easy to calculated according to the properties of 3D Hilbert curve, we only analyze the global trajectory length. The number of localizable sensor nodes reflects the coverage ratio of the mobile anchor to the free space of the region. Obviously, the trajectory should be as shorter as possible, the localizable nodes should be as many as possible, and the accuracy should be as higher as possible.



(a) (b) (c)

Figure 5 Graph G. (a) Common plane; (b) common edge; (c) common point.



(a) (b) (c)

Figure 6 (Color online) Global trajectory. (a) Common plane; (b) common edge; (c) common point.

Table 1 Simulation results

Cube size (m)	Ratio of localization nodes (%)	Length of global trajectory		
		Common plane (m)	Common edge (m)	Common point (m)
50	39.39	1150	1150	1150
40	51.44	3340	3460	3670
25	70.30	8575	8675	8375
20	83.03	14680	14480	27280

4.2 Simulation results and analysis

For Figure 4, the adjacent graph G and corresponding global trajectory are shown in Figures 5 and 6, whose cube is of the side length 40 m. In Figure 6, the double lines illustrate the backtracks of the global trajectory, and the vertices marked with “$*$” and “$\triangle$” are the first and last visited vertex in the global trajectory respectively.

Table 1 shows the numerical results of experiments. Obviously, the smaller the cube to be used in decomposition, the more sensor nodes can be localized, and the longer the global path is. In addition, the adjacent criteria have a significant effect on the trajectory length when the cube size is 25 and 20 m, while the trajectory length is almost the same when the cube size is 50 and 40 m.

Table 2 gives the localization accuracy. We can see that the larger the radio range of mobile anchor, the larger the localization error is. But the ratio of the localization error to the radio range of anchor is all lower than 1%. Thus, this method can localize the sensor nodes with high precision.

Table 2 Localization errors

Ratio range (m)	10	20	30	40	50
Localization error (m)	0.1372	0.1756	0.1753	0.1925	0.2301

5 Conclusion

As one of the key technologies of wireless sensor networks, localization attracts many researches. To make the localization procedure cost-effective, mobile anchor assisted localization methods have been proposed, for which it is very important to design the moving trajectory of the mobile anchor.

This paper has proposed an obstacle-avoidance trajectory planning algorithm in order not to obstruct the free movement of mobile anchor. The proposed method decomposes the deployment region into a number of cubes and translates it into a graph. Successively, a depth-first-search based algorithm with greedy strategy has been proposed to plan the global trajectory while local trajectory adopts the 3D Hilbert curve. Simulation results have shown that the proposed method can avoid the collision of mobile anchor with obstacles and have also demonstrated the high localization precision.

In the future work, movable obstacle should be taken into account when we design the obstacle-avoidance trajectory and new localization algorithms will be proposed for wireless sensor networks, as part of 5G wireless networks [30,31].

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