3D Path Planning Algorithm for Mobile Anchor-Assisted Positioning in Wireless Sensor Networks

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Abstract- **Positioning service is one of Wireless Sensor Networks' (WSNs) fundamental services. The accurate position of the sensor nodes plays a vital role in many applications of WSNs. In this paper, a 3D positioning algorithm is being proposed, using mobile anchor node to assist sensor nodes in order to estimate their positions in a 3D geospatial environment. However, mobile anchor node's 3D path optimization is off the subject. Accordingly, 3D path planning is slightly involved as precision schemes to minimize error boundaries and fault probabilities on mobile wireless anchor's dynamics of precision positioning. In order to analyze proposed 3D path planning scheme's performance, extensive WSNs simulations have been conducted using the NS-2 network simulator. Authors had to extend NS-2's functionality to support 3D geospatial systems, features and calculations. Results indicate that path planning algorithm in discussion, achieves landmark performance and accuracy in average positioning error and percentage of positioned sensor nodes.**

Index Terms- Mobile Anchor Node, Positioning, Wireless Sensor Networks, 3D Path Planning.

I. INTRODUCTION

Sensing is a technique used to gather information about a physical object or process, including the occurrence of events (i.e., changes in a system's state or structural information, such as temperature, volume or pressure). The apparatus unit, performing such a sensing task is called a sensor [1].

Recent forward leaps of technology made development of low-cost, low power, and multifunctional sensor devices, not only possible but also feasible. Autonomous devices with integrated sensing, processing, and communication capabilities [2]. When many networked sensors cooperatively monitor physical environments, they form a wireless sensor network [1].

Manuscript received 25-June-2015 and revised 05-Sept.-2015,
Accepted on 17- Oct.-2015
P- ISSN: 2322-4088
E- ISSN: 2322-3936

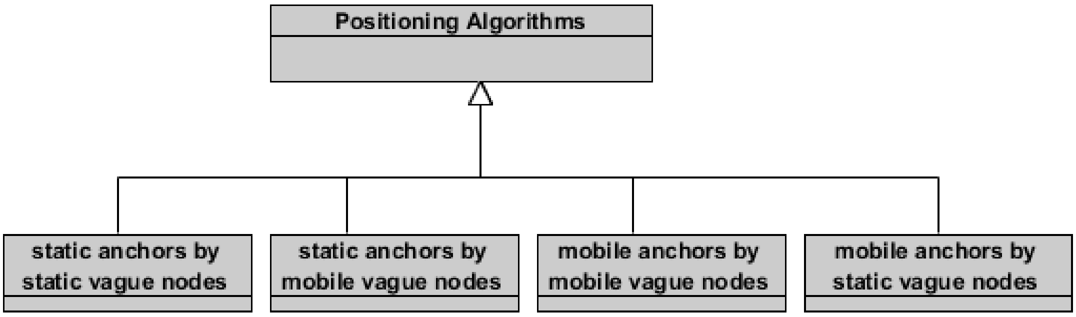

Fig. 1. Proposed classification of WSN's positioning algorithms in [4].

In most of WSN's applications, such as object tracking and environment monitoring, we need to know the position or location of sensor nodes to enrich sensing data into more decision worthy information state. Positioning is the process to compute wireless sensor device node positions in a network [3].

There are two types of sensor nodes in WSNs, one is the anchor node, and the other is the vague node, a node where we have insufficient or outdated information on, positioning wise. The sensor node that is self-position aware through positioning devices like global positioning system (GPS) is referred as anchor node and latter is a node with unknown or vague positions, as so they're called vague nodes. Anchor nodes may be used to identify the location of other unknown nodes in WSNs.

There are few classifications available on positioning algorithms and during [4] authors propose a new taxonomy based on mobility characteristics of anchor and vague nodes. In [4], positioning algorithms are classified into four classes: (1) static anchors by static vague nodes, (2) static anchors by mobile vague nodes, (3) mobile anchors by mobile vague nodes and last but not least, (4) mobile anchors by static vague nodes. This can be seen in Fig. 1. This paper focuses on mobile anchors by static vague nodes class of positioning algorithms.

According to [4], the mobile anchors, static vague nodes positioning algorithms are divided into two classes: geometric principled positioning algorithms and path planning positioning algorithms. Geometric positioning algorithms encapsulate the positioning problem as a geometric problem, and calculate the positions of the vague nodes based on the geometric relationship between mobile anchors and static vague nodes. In path planning positioning algorithms, a mobile anchor node moves along with a specific path and broadcasts its position information to vague nodes.

Positioning algorithms tend to static vague anchors, oftenly based on manageability and cost rationales. However, in case on anchors if all nodes within the network have the ability to determine their locations, a large number of static anchors is apparently required in order to be able to meet and support large scale WSNs requirements. Hence, on midsize to enterprise WSNs level, mobile anchor based positioning algorithms have had a strategic boost up to be promising on methods to reduce network infrastructural, implementation and maintenance costs. Mobile anchors navigate the sensing field and push-send anchor messages to vague nodes. Positioning based on mobile node path planning is a challenge in these methods.

A review of the literature relating to the positioning problem shows that two-dimensional sensor network models have been extensively researched but when it comes to 3D geospatial and topologies, there's an evident significant gap, which is totally inherited from mainstream technology trend toward 3D sensing and modeling. Since the real-world applications of WSNs are in a 3D environment, and time technology era has reached uptrend of 3D and connectivity, this paper focuses on 3D path planning positioning. Accordingly, this paper proposes a 3D path planning method for the mobile anchor used in the positioning algorithm presented by Ou et al. [5].

In [5], anchor mobile nodes are used to enable WSN's nodes to construct two circular cross sections in sensor nodes communication sphere and the intersection of the perpendicular line of these two circular cross sections is then calculated in order to estimate the sensor position. However, in [5], the mobile anchors move randomly through sensing field in accordance with the Random Waypoint (RWP) mobility model, thus it is possible that a few percentage of node's positions cannot be determined. In this way, the proposed path planning scheme is specifically designed to both minimize the sensor node's average positioning error and in the same time to maximize the number of sensor nodes to be subject to precision positioning. Proposed scheme's performance has been assessed by conducting series of simulation processes and scenarios using the NS-2 network simulator [6]. In pursuit of 3D environment simulation, authors have had to extend the original functionality of NS-2, to be capable of 3D support.

The remainder of this paper is organized as follows: Section II discusses related work. Section III presents the 3D path planning scheme proposed in this study for the localization method presented in [5]. Section IV presents and discusses the simulation results. Finally, Section V presents the conclusion.

II. RELATED WORK

A. Mobile anchor 3D path planning

In [7], five deterministic paths, named by Layered-Scan, Layered-Curve, Triple-Scan, Triple-Curve, and 3D-Hilbert are proposed, able to cover a given cubic sensing field in 3D spatial space. These paths applied in weighted centroid positioning method and simulations, upon execution. Results show that every and each one of used paths were more qualified and precise to be implemented than any given random moving path.

In [8], an anchor is equipped with the GPS receiver, and traverses the network along the Hilbert's curve. The sensor nodes estimate their positions using trigonometric method based on the properties of Hilbert's curve.

B. 3D positioning

In [9], a robust 3D positioning algorithm called Landscape-3D, is proposed. In this algorithm, the mobile anchor node flies through the sensing field and broadcasts anchor points periodically. Vague nodes collect the anchor points and measure the distance between self and the mobile anchor node, based on Received Signal Strength (RSS). Then, positions are calculated through Unscented Kalman Filter (UKF)-based algorithms.

In [10], a new positioning algorithm is proposed to improve basic centroid positioning method and can be used in 3D WSNs. The algorithm does not use 2D centroid theorem, and presents the centroid theorem of a coordinate-tetrahedron in the volume-system.

A connectivity-based 3D positioning method is presented for large-scale WSNs with concave regions in [11]. It uses connectivity information and works fine in both 2D and 3D coordinate and spatial spaces. The main idea of the [11] is to discover the notch nodes, where shortest paths bend and hop-count-based distance starts to deviate from the Euclidean distance. [11] Uses a notch-avoiding multilateration method in an iterative way to position nodes in WSNs.

In [12], authors propose a method to utilize four mobile anchors that form a regular tetrahedron while they are traversing the sensing field in a 3D spatial space. Vague sensor nodes estimate their locations using weighted centroid method. Proposed method also presents the layered scan trajectory of mobile anchors.

In [13], an obstacle-avoidance path planning method for 3D WSNs is proposed. The proposed method decomposes the sensing area 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. In fact, the main proposed path of this paper is 3D Hilbert. A trigonal function based positioning method is presented to estimate the positions of the sensor nodes.

III. POSITIONING ALGORITHM

In this section, a technical through description of proposed positioning algorithm, is given. [5] is extensively used in order to analyze effectiveness of proposed 3D path planning.

In [5], the positioning methodology is based on geometric corollary, which postulates that a perpendicular line passing through the center of a sphere’s circular cross section, also passes through the center of that sphere [14]. It is assumed then the communication ranges over which a sensing node can detect broadcasts from the flying anchors are bounded by a spherical surface and that the sensor node is located at the center of this sphere.

As the anchors fly through the sensing space, they broadcast their current positions, and the sensor

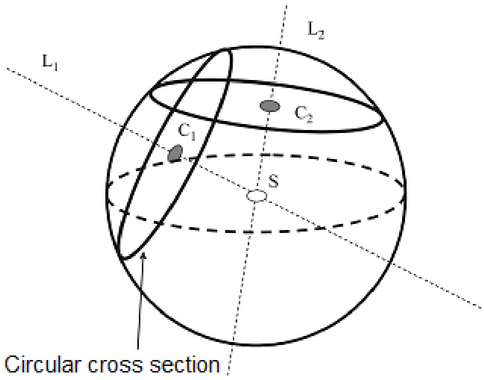

Fig. 2. Location calculation [5].

node chooses the locations of appropriate anchors to form circular cross sections of the sphere. Once two circular cross sections have been constructed, the center of the sphere (i.e., the sensor node position or location) is estimated by calculating the intersection point of the two perpendicular lines passing through the centers of the two circular cross sections, respectively. Fig. 2 shows the sensor position estimation proposed in [5].

There are two research challenges in mobile anchor-based positioning algorithms: one challenge is positioning algorithm itself and the other is path planning for mobile anchor. In [5] there is no solution regarding path planning for mobile anchors. How mobile anchor move in order to provide all nodes with precision positioning doesn't have a solution yet. Hence, mobile anchors movement is considered randomly, according to the RWP trajectory. On this paper, a 3D path planning scheme is proposed based on positioning method in [5].

A. Limitations of existing 3D path planning schemes

In [7], various 3D path planning schemes (Layered-Scan, Layered-Curve, Triple-Scan, Triple-Curve, and 3D-Hilbert) have been proposed for the single mobile anchor and implemented in centroid positioning method. However, these schemes cannot be directly applied to the positioning method proposed in [5]. According to [7], 3D-Hilbert is the best path with the shortest length and minimal average positioning error. 3D-Hilbert cannot guarantee that every node will obtain four or more anchor points required to construct two circular cross sections, required to compute sensor position estimation scenarios.

In [5], authors used RWP mobility model. This way does not guarantee all nodes, for precision positioning and the trajectory of the mobile anchor cannot guarantee that each sensor node can construct two valid circular cross sections. To resolve this problem, based on the Layered-Scan path, authors needed to develop a new 3D path planning method designed to meet the specific requirements of positioning method in [5], namely all sensor nodes gain ability to identify four or more anchors points, to guarantee formation of two circular cross sections.

B. System assumption

In developing of 3D path planning scheme proposed in Ou et al.'s study for positioning method presented in [5], it is assumed that the network consists of static sensor nodes, randomly deployed in an L×L×L field and a single mobile anchor node. It is assumed as well that the mobile anchor node obtains its position coordinates via a GPS receiver and flies through the sensing space transmitting their current locations such that each sensor node can then estimate self-position. The sphere is taken to indicate the sensor node's position, and the radius of the sphere corresponds to the maximum range over which the sensor node can detect the location information broadcast by the mobile anchor.

C. Proposed mobile anchor 3D path planning

If four or more anchor points are obtained from communication sphere of a sensor node, it follows that the mobile anchor node must have passed through the sphere's horizon, on at least two occasions. The appropriate value of horizon pass through events for each sensor node's sphere is either two or three times. Because more than three times values, result in redundant anchor points and information duplication faults.

In proposed 3D path planning scheme, the distance between two successive vertical and horizontal sections of the anchor trajectory (the resolution) is specified as *2R-X*, where *R* is the transmission range of the mobile anchor node. By choosing an appropriate value of *X*, the proposed path planning scheme guarantees that the mobile anchor node passes through the sphere of each sensor node either two or three instants. Accordingly, range computation of *X* follows (Fig. 3):

- The lower bound of *X*:
  $2R - X \leq 2R \Rightarrow 0 \prec X$ and $2R - X \leq R \Rightarrow R \leq X$
- The upper bound of *X*:
  $2R \leq 3(2R - X) \Rightarrow X \leq \frac{4}{3}R$

Thus, *X* is bounded in range $0 < R \leq X \leq \frac{4}{3}R$.

This is because if *X* yields bigger than $\frac{4}{3}R$, the mobile anchor node will pass through the sphere of node more than three times and then results in redundant anchor points, as explained earlier. In contrary, decreasing the value of *X* may cause the number of anchor points to fall off below minimum required points. Hence, in practice, a careful choice of *X* is required.

The proposed 3D path planning scheme based on Layered-Scan is shown in Fig. 4. As shown in Fig. 4, the length of the full path, *P* is given as

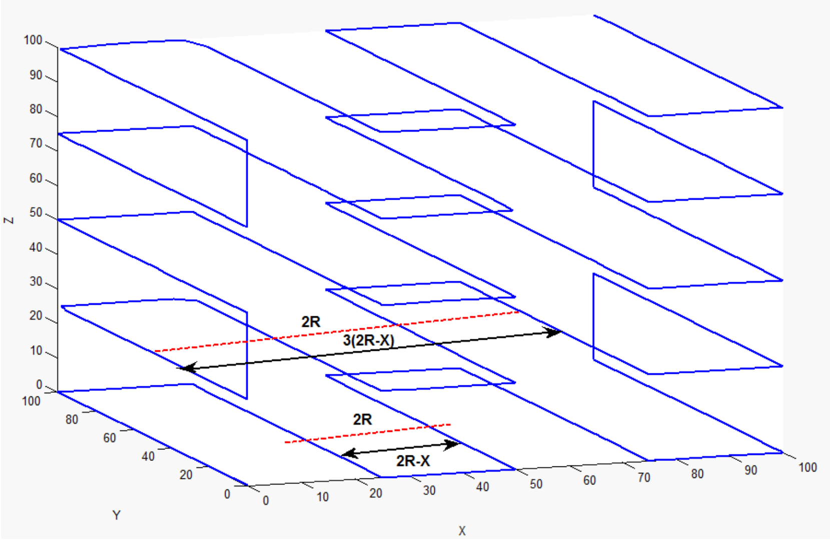

Fig. 3. Computation of the lower and upper bounds of X.

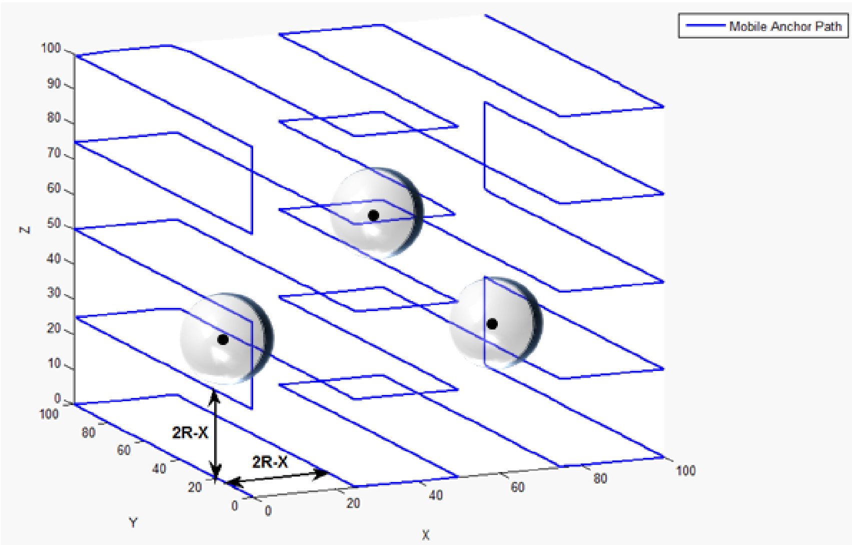

Fig. 4 Proposed 3D mobile anchor path.

$$P = L \times \left\lceil \frac{L}{2R-X} \right\rceil \times \left(\left\lfloor \frac{L}{R} \right\rfloor + 1 \right) + (2R-X) \times \left\lceil \frac{L}{2R-X} \right\rceil \times \left(\left\lfloor \frac{L}{R} \right\rfloor + 1 \right) + \left(\left\lfloor \frac{L}{R} \right\rfloor \times (2R-X) \right) \qquad (1)$$

As shown, the path length P comprises three components. A vertical path, a horizontal path and a height path component. The vertical path component comprises $\left\lceil \frac{L}{2R-X} \right\rceil$, quantity of sections of length L multiplied by quantity of layers $(\left\lfloor \frac{L}{R} \right\rfloor + 1)$, while the horizontal path component comprises $\left\lceil \frac{L}{2R-X} \right\rceil$, quantity of sections of length *2R-X*, multiplied by quantity of layers $(\left\lfloor \frac{L}{R} \right\rfloor + 1)$, and height path component comprises $\left\lfloor \frac{L}{R} \right\rfloor$, quantity of sections of length *2R-X*.

As shown in Theorem 1, later on next paragraph, the proposed path planning scheme guarantees that all the sensor nodes in the sensing field, have enough updated, information to estimate their positions.

Theorem 1: All sensor nodes can estimate their positions.

Proof: In the positioning method proposed by Ou et al., in [5], a minimum of four anchor points is required for each sensor node to estimate its position. If a sensor node is unable to determine its position, it shows that the mobile anchor node has not been flown through the communication range of sensor node or even mobile anchor might have flown through the communication range of sensor, but the number of the anchor points is less than four anchors. This situation cannot arise in the 3D path planning scheme proposed in current study since the distance between two adjacent vertical and horizontal paths is specified as *2R-X* and *X* are assigned a value in the range $0 < R \leq X \leq \frac{4}{3}R$. As a result, the mobile anchor node is guaranteed to pass through each sphere on at least two occasions, and thus each sensor node can always obtain a minimum of four anchor points. As end results, all the sensor nodes are able to determine their positions. ■

IV. PERFORMANCE EVALUATION

A series of simulations has been conducted using the NS-2 network simulator [6] for evaluating the performance of the proposed 3D path planning scheme. In order to generate 3D RWP mobility model, authors have used BonnMotion tool [15].

The NS-2 does not support 3D environment. Therefore, authors have been added 3D capability to it. In order to do this, some modifications were required. Those were:

- Extension of WSN's environment to support 3D topology, by adding Z dimension to "Topography" class (a sensor node needs to move in 3D space; therefore, a 3D topography needs to be defined).
- Extension of sensor node position to 3D by implementing Z dimension to "mobilenode" class.
- Extension of sensor node mobility to 3D by adding Z dimension to "setdest" class (Defining new "set_destination3d" method in "mobilenode" header, which takes X, Y, Z destination positions of a sensor node along with mobility speed).

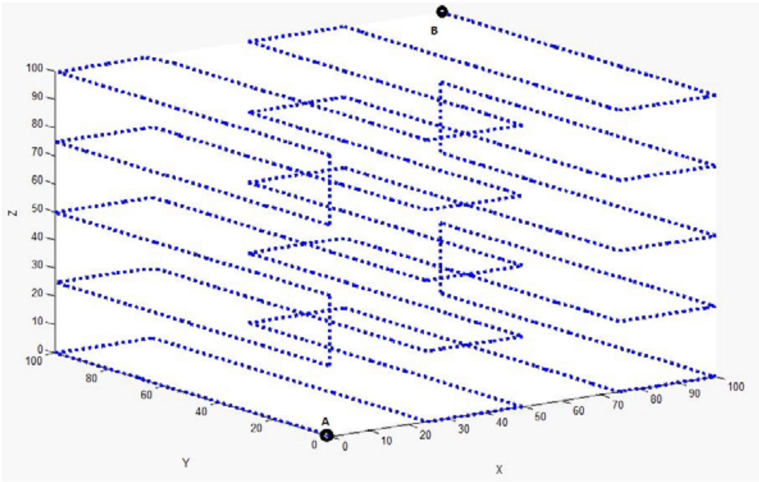

Fig. 5. Sensing field.

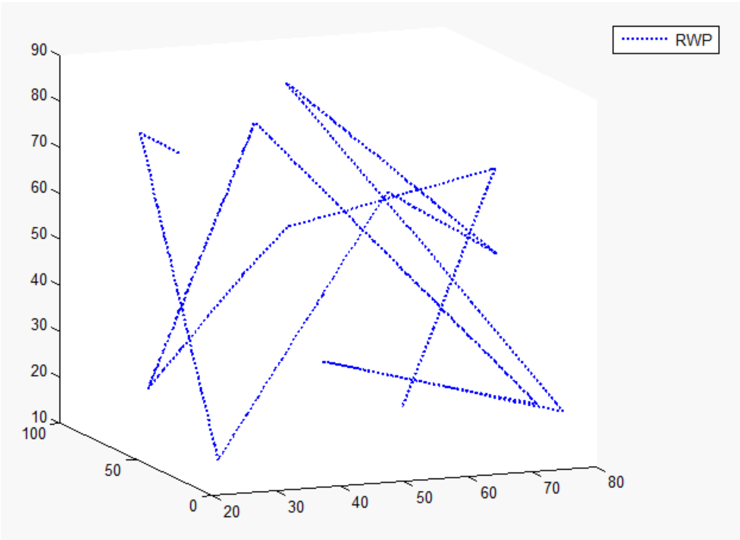

Fig. 6. The RWP trajectory.

A. Scenarios and parameters

Proposed 3D path planning scheme's performance was analyzed and compared with that of Layered-Curve, Triple-Curve, 3D-Hilbert, and the original RWP movement scheme's peer, by Ou et al. in [5]. To ensure a fair comparison, time value of RWP movement scheme was set equal to that of original proposed scheme, in [5].

Sensing area is a cube of side L = 100 m, where N = 100 vague nodes are randomly deployed, along with a single mobile anchor node (see Fig. 5).

During simulations, the mobile anchor node commenced at point A and ended at point B based on the proposed path planning.

The other parameters during the simulation are expressed as follows. The radio range of anchor is a sphere of R = 35 m. The anchor moves at speed of v = 5 m/s. The resolution of the paths is l = 25 m.

The minimum and maximum speed values of mobile anchor using RWP is v min = 0.5 m/s and v max = 5 m/s. This trajectory has generated using BonnMotion tool. The first step is "Scenario generation" with "RandomWaypoint3D" model and the second step is "Converting scenarios to NS-2 format". Fig. 6 shows the RWP trajectory.

B. Evaluation criteria

The performance of the various path planning algorithms was evaluated using two criteria:

1) The average positioning error: the average distance between the estimated sensor node location (xe_i, ye_i, ze_i) and the actual sensor node location (x_i, y_i, z_i) for all the sensor nodes;

$$\text{Average positioning error} = \frac{\sum\sqrt{(xe_i - x_i)^2 + (ye_i - y_i)^2 + (ze_i - z_i)^2}}{\#\, of\ sensors} \quad (2)$$

2) The percentage of positioned sensor nodes: the ratio of the number of successfully positioned sensor nodes to the total number of sensor nodes;

$$\text{Percentage of localized sensor} = \frac{\# localized\ sensor}{\# of\ sensors} \times 100 \quad (3)$$

C. Simulation results

To ensure the reliability of the assessment results, 10 simulation analysis process run were performed with 10 different initial random deployments of the sensor nodes as WSN. Proposed 3D path planning's performance evaluation result infographics are illustrated and explained thoroughly in the following subsections.

1) Average positioning error

Fig. 7 compares the average positioning errors of the five path planning schemes. On each of 10 simulation processes running, can be seen that when the positioning scheme presented in [5] is implemented using the proposed 3D path planning, the average positioning errors are lower than that of achieved by any of the other schemes. As discussed in Sec. III-A, the remaining path planning schemes are not directly compatible with the localization method presented in [5], and therefore yield relatively poor localization performance. In these schemes, the positioning error is high since anchor points obtained from anchor nodes trajectories cannot guarantee the circular cross section selection threshold, mandated in [5], on each case!

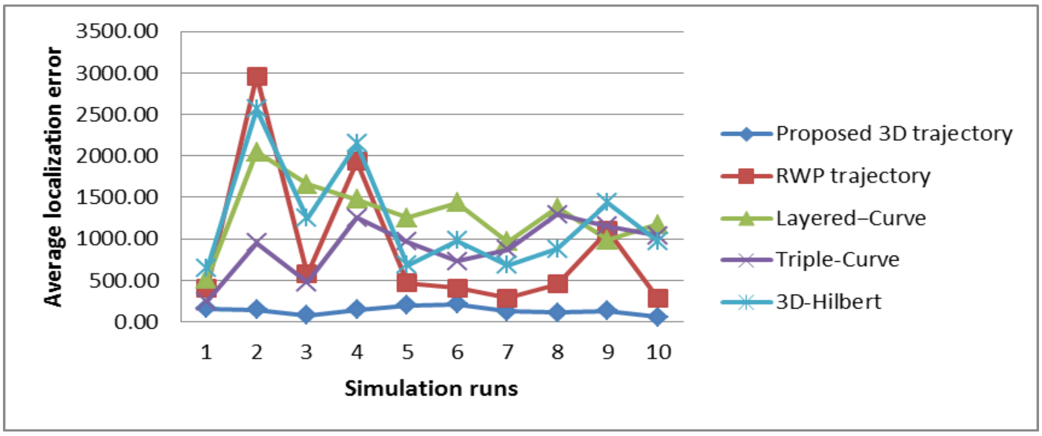

Fig. 7. Average positioning error.

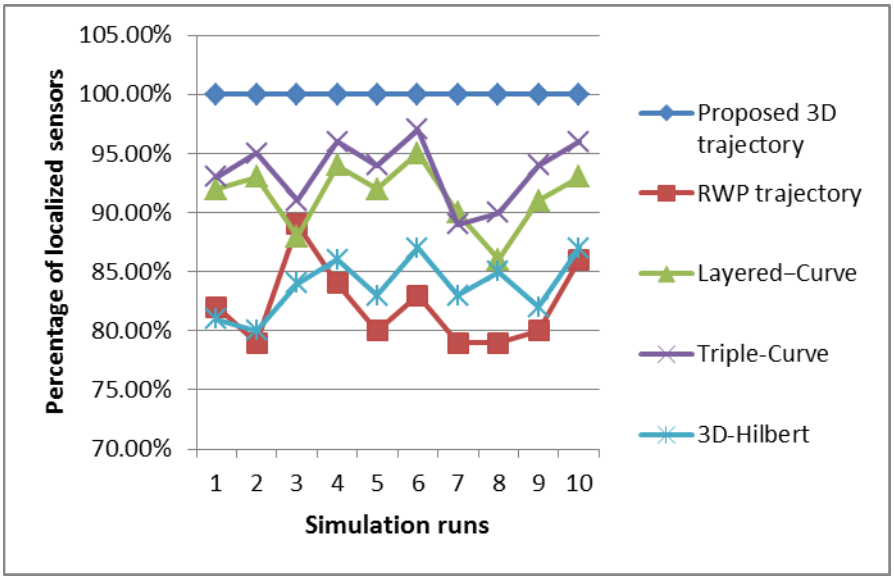

Fig. 8. Percentage of localized sensor nodes.

2) Percentage of positioned nodes

Fig. 8 shows the percentage of precisely positioned sensor nodes on each simulation running. It's observed that the 3D path planning proposed by this paper enables all the sensors to determine their locations or positions, in every simulation running. The remaining schemes, i.e., Layered-Curve, Triple-Curve, 3D-Hilbert, and RWP mobility model, result in average localization percentages of 91%, 93%, 83%, 82%, respectively. In fact, the RWP results in the lowest percentages of localized nodes.

According to Fig. 8, there are some sensor nodes in remaining trajectories that they have not been positioned, the reason as explained earlier is inadequate quantity of cross encounter between flying mobile anchor nodes and sensor node's communication sphere.

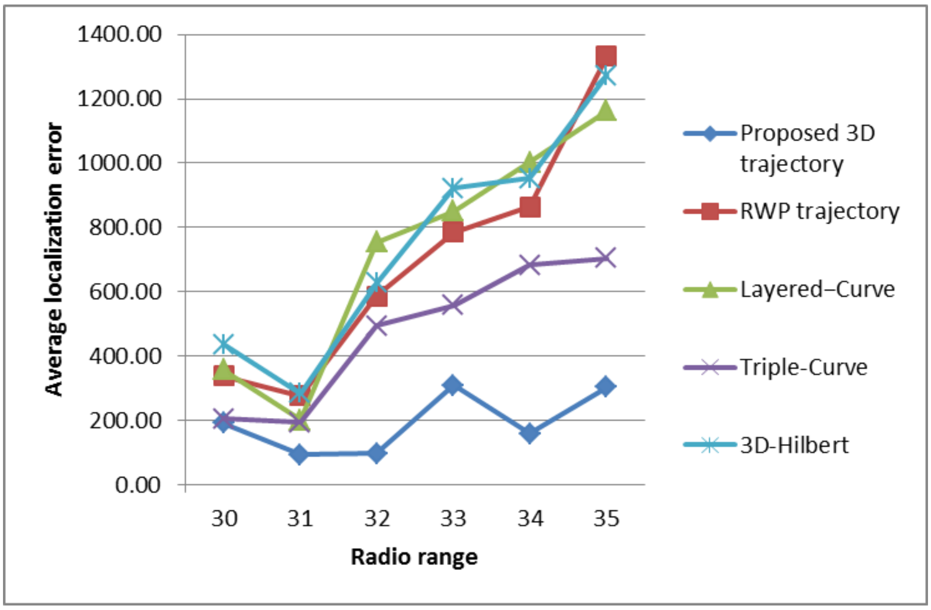

Fig. 9. Radio range versus average positioning error.

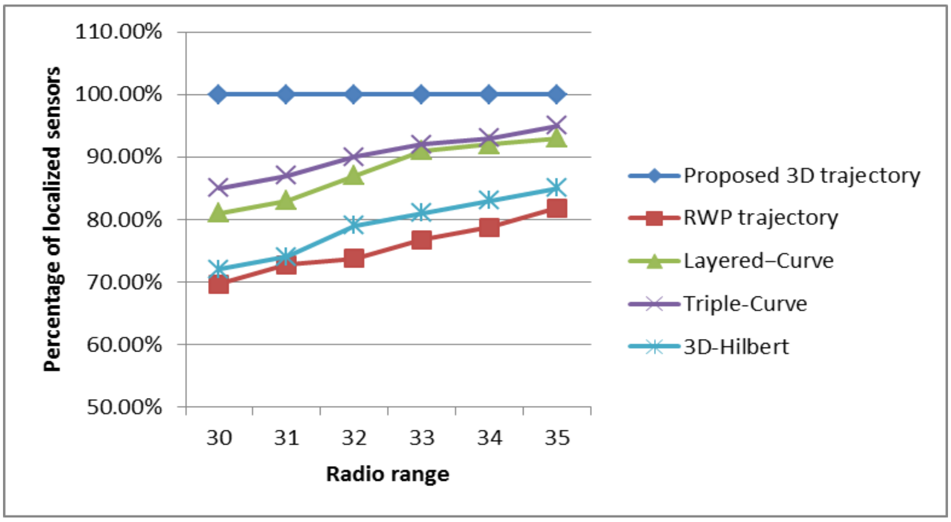

Fig. 10. Radio range versus percentage of positioned sensor nodes.

1) Impact of radio range

The performance was studied and compared with other schemes for radio ranges of 30 to and 35 m. In fact, the impact of radio range versus average positioning error and percentage of positioned sensor nodes were analyzed.

As shown in Fig. 9, the average positioning error of the other schemes increase significantly as radio ranges increase. However, the average positioning error of current paper’s proposed scheme improves slightly as the radio range increases.

As shown in Fig. 10, the percentage of positioned sensor nodes in other schemes, increases significantly, as the radio range increases.

V. CONCLUSION

Mobile anchor assisted positioning algorithms have attracted attentions in WSNs research areas and communities, recently. On the topic, there are two challenges. One is positioning algorithm and latter is path planning of mobile anchor for precise positioning.

In this paper, we have proposed 3D path planning based on positioning algorithm in [5]. The performance of the proposed scheme has been compared with Layered-Curve, Triple-Curve, 3D-Hilbert, and RWP in terms of average positioning error and percentage of positioned nodes. The simulation results have shown that the proposed 3D path planning scheme, outperforms existing methods in terms of both used analytic criteria. We also have had to modify the NS2 in order to implement and enable 3D capabilities.

The future work will study the anchor selection procedure by a machine learning approach to form best of two circular cross sections to improve precision and reduce positioning errors.

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