

Flexible Localization Method with Motion Estimation for Underwater Wireless Sensor Networks

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Abstract—Due to the challenging conditions of underwater environments, such as node mobility and large-scale networks, achieving localization in large-scale mobile underwater sensor networks (UWSN) is a difficult task. This paper introduces a scheme known as the Flexible Localization Method with Mobility Estimation (FLMME) for UWSNs by utilizing the expected mobility patterns of underwater objects. FLMME performs localization hierarchically by splitting the process into anchor and ordinary node localization. Each node estimates its next mobility pattern based on previous location information, enabling estimates about its next location. Anchor nodes, holding known locations, manage the localization process to balance accuracy and error trade-offs. Extensive simulations demonstrate that FLMME reduces localization errors and hence increases localization accuracy.

Keywords— Underwater Wireless Sensor Networks (UWSN), Localization, Movement Estimation, Tracking, Sensor Deployment

I. INTRODUCTION

Approximately 70% of Earth's surface comprises ocean, river, and sea, that drawing global focus toward harnessing its resources. Underwater wireless sensor networks (UWSNs) have become essential to oceanic advancements. They are self-organizing networks of small-sensor nodes deployed in oceanic monitoring areas, enabling real-time and precise underwater environment monitoring [1]. UWSNs are widely applied in water environment monitoring, disaster prediction, marine navigation, military applications, and seabed exploration. Accurate knowledge of UWSN node locations is crucial for tasks like topology control, coverage, and routing decisions. Hence, UWSN localization research is of essential significance [2]–[4].

Localizing mobile nodes within UWSNs holds significant importance in various domains. In marine military defense, it's vital for identifying and tracking intrusion objects. For animal tracking, it aids in observing marine animals' locations and movements. Mobile node localization extends the monitoring area, proving valuable in marine environmental monitoring by identifying potentially polluted areas and covering extensive

regions. Effective path planning and optimizing underwater node coverage depend on localizing mobile nodes, given the significance of location in managing data collection and transmission in sensor networks. As a result, localizing mobile sensor nodes has become a prominent research focus.

Overcoming major challenges in underwater localization, including substantial acoustic channel delays and high signal attenuation in RF/optical channels, is crucial. The primary challenges include (1) Node mobility concerns driven by water currents, turbulence, and winds that displace sensor nodes from their positions. While GPS can locate surface buoy-based anchor nodes, underwater node location measurement remains difficult [5]. (2) Sensor node deployment is critical in network establishment but challenging in harsh underwater conditions. (3) Achieving synchronization without GPS signals poses a challenge, leading to significant localization errors in time-of-arrival-based ranging due to lack of synchronization [6], [7].

In this paper, we introduce an approach for underwater sensor network localization, which we call a Flexible Localization Method with Motion Estimation (FLMME). FLMME employs a hierarchical localization process by dividing it into two stages: localizing anchor nodes and ordinary sensor nodes. Each node in the localization process makes predictions about its next movement patterns based on prior known location data, enabling it to estimate its next location. To balance the compromises between the localization error, coverage, and accuracy, the known location of anchor nodes within the network will manage the localization procedure. Simulation outcomes demonstrate that FLMME significantly reduces localization error while preserving high localization accuracy and coverage.

The rest of the paper is organized as follows: the classification of localization techniques for UWSN is given in Section II, then the network architecture and proposed FLMME algorithms are described in Section III. In Section IV, the simulation results are presented. Finally, the paper is included in Section V.

II. CLASSIFICATION OF LOCALIZATION TECHNIQUES FOR UWSN

Addressing the aforementioned challenges, researchers have developed diverse localization algorithms suitable for UWSNs. These algorithms can be categorized based on various data acquisition and processing approaches. In this section, we divided the localization schemes into five categories: range-based, range-free, network-based topology, centralized, and distributed localization schemes, as seen in Figure 1. Each category will be explained with some examples as follows:

- 1) **Range-based Localization:** The ranging-based algorithm employs varied techniques, such as Angle of Arrival (AOA), Time of Arrival (TOA), Received Signal Strength Indication (RSSI), and Time Difference of Arrival (TDOA), to measure node distances to anchor nodes and determine unknown node locations [8]–[10]. TOA, reliant on signal transmission time and speed, requires network-wide time synchronization, providing more accuracy in underwater localization due to faster wireless acoustic signal propagation. TDOA calculates node distances based on signal arrival time differences and respective velocities, exhibiting higher accuracy with demanding hardware requirements. RSSI translates signal loss into distance, cost-effectively, without the need for time synchronization, yet environmental variations affect its accuracy. The AOA algorithm mandates node-deployed antennas to gauge received signal angles for node coordination, entailing additional costs and posing scalability challenges [11]–[13].
- 2) **Range-free Localization:** The range-free algorithms estimate node distances based on hop count and directional data, converting this information into approximate node positions. However, these methods generally lack precise localization and typically offer only approximate node estimations [14]. Examples include DV-Hop, Center-of-mass (CoM), and APIT [15]–[17]. DV-Hop relies on hop count to calculate node distances. It calculates the minimum hops to the anchor node, estimates the average hop distance, and multiplies these to approximate the unknown node's position. CoM requires a node to select several anchors within its communication range, gathering their information. Upon reaching a set threshold, it calculates the center-of-mass coordinates based on the coordinates of the anchor nodes. Although straightforward, the CoM method lacks high localization accuracy.
- 3) **Network-based Topology Localization:** in which the localization algorithms are categorized into two primary types based on network topology and node connectivity: single-hop and multi-hop. Single-hop localization describes instances where an unknown node communicates directly with an anchor node within a single-hop distance. In contrast, multi-hop localization requires unknown nodes to pass through multiple nodes to reach the anchor node. While single-hop algorithms demand a high density of anchor nodes, resulting in substantial

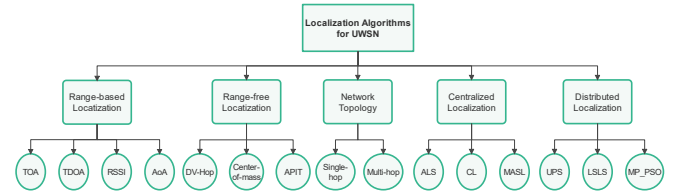


Figure 1: Localization techniques for UWSN

costs, multi-hop algorithms, requiring nodes to relay information through intermediaries, offer a more cost-effective and feasible solution for wider network coverage.

- 4) **Centralized Localization:** In a centralized localization approach, all nodes transmit collected data to a central sink node for processing. Equipped with significant computational power, the sink node calculates the positions of unknown nodes and relays this information back. However, due to the substantial computational load on the sink node, this approach is best suited for small-scale UWSNs, resulting in high energy consumption. Common methods include Area-Based Localization Scheme (ALS), Collaborative Localization (CL), and Motion-Aware Self-Localization (MASL) [18], [19].
- 5) **Distributed Localization:** The distributed localization method involves nodes processing their information autonomously and then interchanging this data for localization, making it ideal for large-scale UWSNs. This enables real-time node position retrieval while distributing computational tasks across the network. Well-known distributed localization approaches include the Underwater Positioning Scheme (UPS), Large-Scale Localization Scheme (LSLS), and Localization based on Mobility Prediction and Particle Swarm Optimization (MP-PSO) [20], [21].

III. DESCRIPTION OF FLMME ALGORITHM

First, this section outlines the network architecture of large-scale UWSNs, followed by an overview of the FLMME algorithm, and then the anchor node mobility estimation and the ordinary node localization are described in detail.

A. Network Architecture

To perform node localization within large-scale UWSNs, a hierarchical network structure is introduced and illustrated in Figure 2. This architecture involves three node types as follows:

- **Surface buoys:** These are located on the ocean surface and achieve precise location data through GPS systems. They are responsible for aiding in the localization of anchor nodes.
- **Anchor nodes:** These are high-energy devices that communicate directly with buoy nodes to determine their positions. They move in concurrence with the water current. These high-energy anchor nodes tend to be costly. So, to

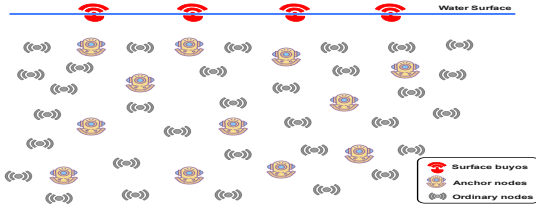


Figure 2: UWSN architecture with different node types

mitigate expenses, this network includes only a limited number of anchor nodes (10).

- Ordinary Sensor nodes: Prior to the localization process, all nodes, excluding buoys and anchor nodes, are categorized as ordinary nodes. Similar to anchor nodes, these ordinary nodes inertly drift with the water current. They are unable to connect with buoys directly and are not all within the coverage of anchor nodes. Only ordinary nodes within the communication range of an anchor node can ascertain their location via these anchors [22].

To summarize, anchor nodes acquire their locations directly through communication with surface buoys, while ordinary nodes self-localize by interacting with neighboring anchors or ordinary nodes. Each sensor node is anticipated to periodically obtain its location, denoted as the localization period T_1 . This assumption is realistic in various applications, like environmental monitoring, where sensor nodes periodically transmit observed data to the sink. Location information at these specific time points proves to be particularly relevant.

B. Overview of FLMME

FLMME utilizes a hierarchical localization strategy. This approach separates the overall localization procedure into two parts: (1) localization of anchor node and (2) localization of ordinary node. Initially, a limited number of surface buoys possess their locations through GPS or alternative methods. In this network, at least four buoys are required to enable the localization of anchor nodes. As the anchor nodes possess higher capabilities, they directly determine their positions from the surface buoys within each localization period. This allows the implementation of intricate mobility estimation algorithms on these anchor nodes.

We introduce a distributed range-based approach for the localization of ordinary nodes, detailed in Section III-D. As ordinary nodes have constrained computational power and memory, intricate estimation algorithms are challenging to implement on them. However, owing to the collective movement characteristics of underwater entities, an ordinary node can infer its movement pattern by observing the movement patterns of neighboring nodes. The ordinary node actively listens for localization messages within the network. If it does not receive any messages beyond a predefined duration, it assumes it is out of range, marking itself as unlocalized. Conversely, upon receiving localization messages, the node initiates its localization and movement estimation algorithm to estimate its location and movement pattern. The estimation algorithm will be elaborated in Section III-D.

C. Mobility Estimation of Anchor Nodes

In the beginning, anchor nodes have the advantage of direct communication with surface buoys, enabling them to obtain their actual locations at any localization period. Additionally, these nodes can estimate their next mobility patterns based on previous measurements. In localization period T_1 , the anchor node can calculate its actual location as $Anchor_{Actual}(T_1)$, then it can estimate its location as follows:

$$Anchor_{Estimated}(m) = Anchor_{Actual}(m-1) + T_1 * v(m-1) \quad (1)$$

where $Anchor_{Actual}(m-1)$ is the actual location of the anchor node at the time $(m-1)T_1$ and $v(m-1)$ is the estimated speed of the anchor node in the localization period $(m-1)$.

Then, according to the anchor node's actual and estimated locations, the localization error can be obtained as follows:

$$Anchor_{Error}(m) = Anchor_{Estimated}(m) - Anchor_{Actual}(m) \quad (2)$$

where $Anchor_{Actual}(m)$ is the actual location of anchor node at mT_1 . After that, the anchor node assists in the localization of ordinary nodes by transferring its mobility information through synchronous transmission.

D. Localization of Ordinary Nodes

To estimate the accurate next location of ordinary nodes, we need the location and the movement speed of the anchor nodes as reference nodes, in addition to the previous locations of the ordinary nodes. In contrast to anchor nodes, the prior location of ordinary nodes is unidentified. Consequently, the initial location of each ordinary node i needs to be determined. To calculate the initial location of ordinary nodes, we need to calculate the distance of the ordinary node from three anchor nodes at time t as follows:

$$d_1 = \sqrt{(X_1 - x_i)^2 + (Y_1 - y_i)^2 + (Z_1 - z_i)^2} \quad (3)$$

$$d_2 = \sqrt{(X_2 - x_i)^2 + (Y_2 - y_i)^2 + (Z_2 - z_i)^2} \quad (4)$$

$$d_3 = \sqrt{(X_3 - x_i)^2 + (Y_3 - y_i)^2 + (Z_3 - z_i)^2} \quad (5)$$

where (X_1, Y_1, Z_1) , (X_2, Y_2, Z_2) , (X_3, Y_3, Z_3) are the anchor nodes real-time location that can be determined through surface buoys, and (x_i, y_i, z_i) is the location of ordinary node at time t . Then, by solving those equations to obtain the current location of the ordinary node. Then, we calculate the movement speed of the ordinary node by using the previous location $(x_{i-1}, y_{i-1}, z_{i-1})$ with the current location (x_i, y_i, z_i) as follows:

$$v = \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2}}{t - (t-1)} \quad (6)$$

According to the mobility of the ordinary node, then the estimated location of the ordinary node can be calculated as follows:

$$Ordinary_{Est}(m) = Ordinary_{Act}(m-1) + T_1 * v(m-1) \quad (7)$$

where $Ordinary_{Est}(m)$ is the estimated location of ordinary node at the time mT_1 , $Ordinary_{Act}(m-1)$ is the location

of the ordinary node at time $(m-1)T_1$, and $v(m-1)$ is the movement speed at time $(m-1)T_1$.

IV. SIMULATION AND RESULTS

This section conducts MATLAB simulations to validate the efficacy of the FLMME algorithm. Table I illustrates the additional parameters utilized in the simulation experiments.

In the subsequent simulation, a total of 100 ordinary nodes and 10 anchor nodes are deployed randomly in a 3D monitoring area of 500m * 500m * 500m. Figure 3 shows the deployment of the anchor nodes and the ordinary nodes at the beginning of the simulation. Node density is considered as the estimated number of sensor nodes within a node's proximity. As a result, the degree of each sensor node and its density are the same. To manage node density, we alter each sensor node's communication range while keeping a similar deployment area. We assume that the estimated distances between sensor nodes conform to normal distributions. This assumption is realistic and aligns with present technologies for measuring underwater distances.

To validate the localization accuracy of the FLMME algorithm, the evaluation metric employed is the localization error (LE), which is defined as the mean distance between the estimated locations and the actual locations of all nodes. The localization error of an individual node is expressed as follows:

$$LE = \sqrt{(X_{Act} - X_{Est})^2 + (Y_{Act} - Y_{Est})^2 + (Z_{Act} - Z_{Est})^2} \quad (8)$$

where $(X_{Act}, Y_{Act}, Z_{Act})$ is the actual location and $(X_{Est}, Y_{Est}, Z_{Est})$ is the estimated location.

Therefore, in UWSN, the average localization error (ALE) for the N localized ordinary nodes is given by:

$$ALE = \frac{1}{N} \sum_{i=1}^N \sqrt{(X(i)_{Act} - X(i)_{Est})^2 + (Y(i)_{Act} - Y(i)_{Est})^2 + (Z(i)_{Act} - Z(i)_{Est})^2} \quad (9)$$

TABLE I: SIMULATION PARAMETERS

Simulation Parameter	Value
Test area	500 m * 500 m * 500 m
Ordinary nodes	100 to 250
Anchor node number	10
Localization period	1 s
Communication range of anchor nodes	200 m
Communication range of ordinary nodes	100 m
Acoustic wave speed	1500 m/s

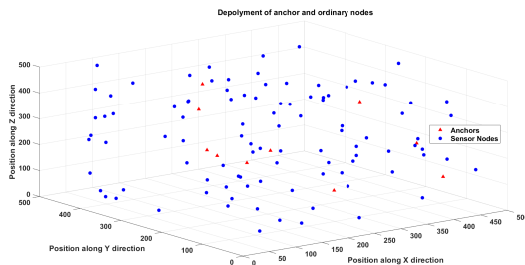


Figure 3: Deployment of 10 anchors and 100 ordinary nodes

A. Impact of Node Density on Localization Results

In this study, we analyze the impact of the node density (increasing the number of nodes) on the localization performance. The localization results of moving sensor nodes due to the water currents are shown in Figures 4 to 7. Hence, increasing the node density leads to decreasing the average localization error and, therefore, increasing the localization accuracy of our method.

Figure 4 presents the simulation for 100 ordinary nodes and 10 anchor nodes. Figure 4a presents the movement of the anchor nodes, and we utilized the range-based algorithm to estimate the next location of anchor nodes and then calculated the average localization error between the actual and the estimated locations and found that the accuracy of the anchor nodes is good which helping in increasing the localization accuracy of the ordinary nodes. Figure 4b shows the relation between the estimated and the actual locations of the ordinary nodes with an average localization error of 107.90 m. While Figure 4c presents the localization results for all anchor and ordinary nodes.

Figure 5 presents the simulation for 150 ordinary nodes and 10 anchor nodes. Figure 5a presents the movement of the anchor nodes, and we utilized the range-based algorithm to estimate the next location of anchor nodes and then calculated the average localization error between the actual and the estimated locations and found that the accuracy of the anchor nodes is good which helping in increasing the localization accuracy of the ordinary nodes. Figure 5b shows the relation between the estimated and the actual locations of the ordinary nodes with an average localization error of 97.86 m. While Figure 5c presents the localization results for all anchor and ordinary nodes.

Figure 6 presents the simulation for 200 ordinary nodes and 10 anchor nodes. Figure 6a presents the movement of the anchor nodes, and we utilized the range-based algorithm to estimate the next location of anchor nodes and then calculated the average localization error between the actual and the estimated locations and found that the accuracy of the anchor nodes is good which helping in increasing the localization accuracy of the ordinary nodes. Figure 6b shows the relation between the estimated and the actual locations of the ordinary nodes with an average localization error of 84.60 m. While Figure 6c presents the localization results for all anchor and ordinary nodes.

Figure 7 presents the simulation for 250 ordinary nodes and 10 anchor nodes. Figure 7a presents the movement of the anchor nodes, and we utilized the range-based algorithm to estimate the next location of anchor nodes and then calculated the average localization error between the actual and the estimated locations and found that the accuracy of the anchor nodes is good which helping in increasing the localization accuracy of the ordinary nodes. Figure 7b shows the relation between the estimated and the actual locations of the ordinary nodes with an average localization error of 69.43 m. While Figure 7c presents the localization results for all anchor and ordinary nodes.

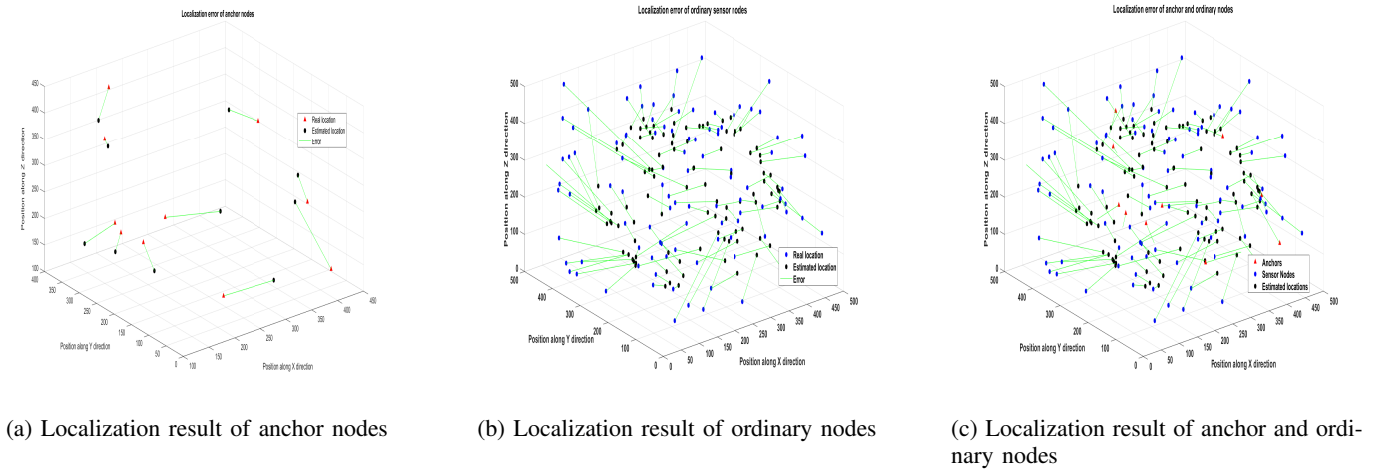


Figure 4: Localization results when the number of nodes=100, anchor nodes=10, and the localization error is 107.90 m

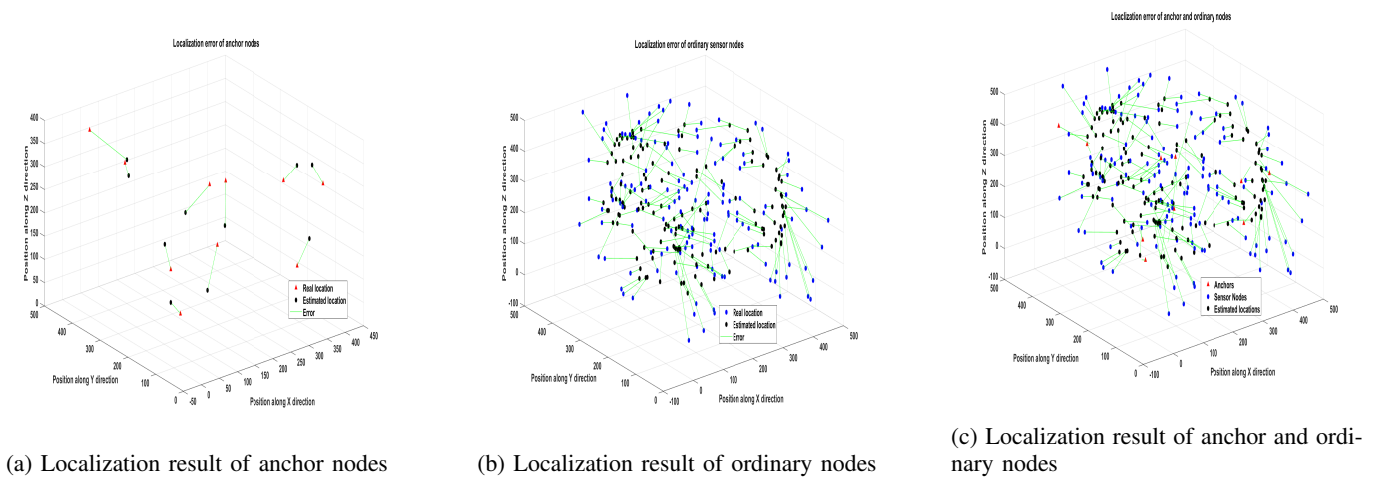


Figure 5: Localization results when the number of nodes= 150, anchor nodes= 10, and the localization error is 97.86 m

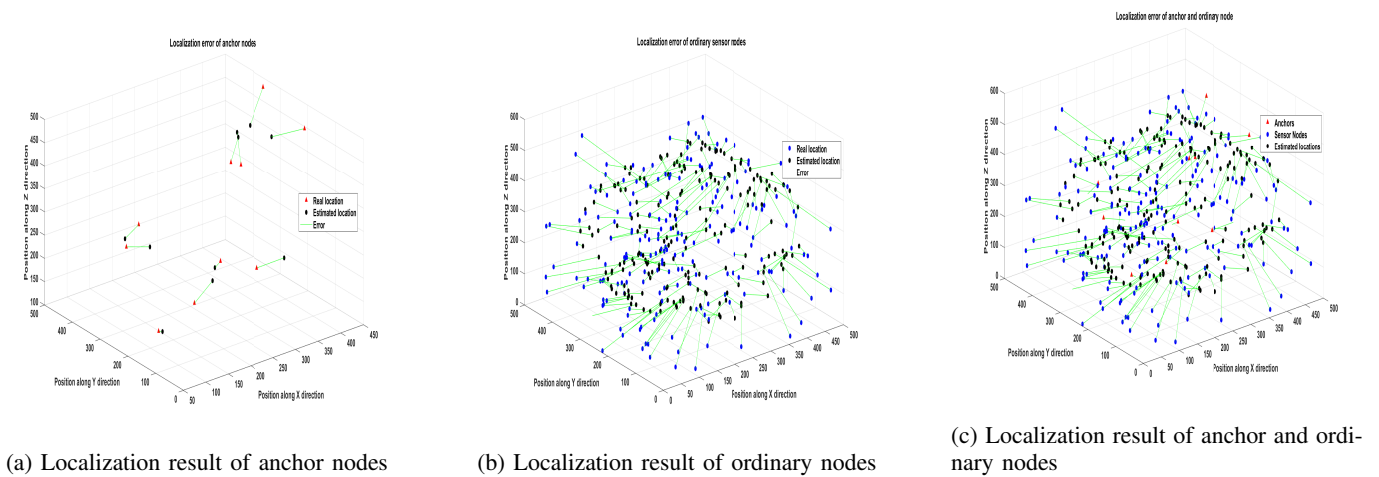


Figure 6: Localization results when the number of nodes= 200, anchor nodes= 10, and the localization error is 84.60 m

V. CONCLUSIONS

This paper presented FLMME, a localization scheme for UWSNs. FLMME utilized the mobility patterns in underwater

environments and employed a hierarchical approach. FLMME divided the localization process into anchor and ordinary node

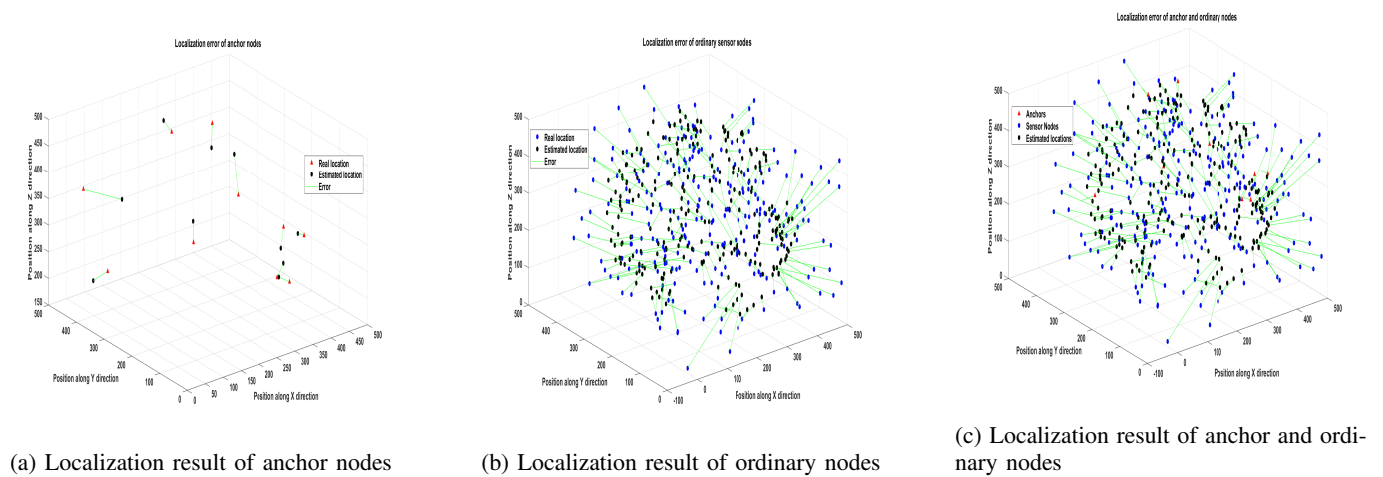


Figure 7: Localization results when the number of nodes= 250, anchor nodes= 10, and the localization error is 69.43 m

localization, enabling each node to estimate its next mobility based on previous location data. Anchor nodes, with recognized locations, guide the process to balance accuracy and potential errors. Extensive simulations demonstrated FLMME's ability to significantly reduce localization errors, enhancing the overall accuracy of the localization process.

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