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CONFERENCE PAPER

A COMPREHENSIVE SURVEY OF RECENT ADVANCES AND EMERGING CHALLENGES IN UNDERWATER SENSOR NETWORK LOCALIZATION

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Abstract

In sensor networks it is really important to know exactly where each sensor node is. This is calledlocalization. We need to figure out where each node is. There are a lot of ways to do this on land but not many of these ways work for sensor networks. This is because underwater sensor networks are very different from the ones on land. Underwater sensor networks have problems withhow they communicate. The sound waves they use to talk to each other are slow. Can only carry a little bit of information at a time. This makes it hard to find the spot of each sensor node. This paper is about the ways we can find the location of sensor nodes in underwater sensor networks. It also talks about the challenges we face when we try to make these networks work for things, like offshore engineering. Underwater sensor networks have a lot of issues that make localization really tough.

Introduction:-

The use of low-cost sensors is a great solution for manyapplications.In environments these applications include early warning systems for natural disasters like tsunamis monitoring the environment and ecosystem oil exploration and military surveillance.However managing large-scale wireless sensor networks is tough because individual sensor nodes have limited processing power and strict power limits.Researchers have been studying issues related to sensor networks from the physical layer to the application layer.One important use of sensor networks is in offshore engineering as shown in Figure 1.Oil exploration vessels are structures anchored to the seabed using multiple anchoring systems often at depths over 3000 meters.In environments smart sensors can be deployed on the seabed to monitor environmental and structural parameters.These sensors work with Remotely Operated Vehicles (ROVs) which are controlled from the surface vessel and Autonomous Underwater Vehicles (AUVs) which navigate environments on their own based on predefined instructions.In this system, sensors, anchors and ROVs/AUVs collect data from the seabed. Send it to the surface vessel.The deployed sensors and anchors measure parameters like foundation stability and mooring tension.

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They also provide positional references to AUVs doing deep-sea exploration using advanced sensing equipment.To work effectively a reliable mechanism for data transmission from the seabed to the vessel is essential.

Accurate localization of sensors, anchors and underwater vehicles is also crucial which is particularly challenging in deep-water environments.The sensors help to monitor the seabed and send data to the vessel.The AUVs and ROVs help with exploration.The anchors help to keep the sensors stable.The vessel gets the data from the sensors. Makes decisions.Underwater sensor networks are useful, for applications.They help with oil exploration and environmental monitoring. The use of sensor networks is increasing.They are used in offshoreengineering scenarios.

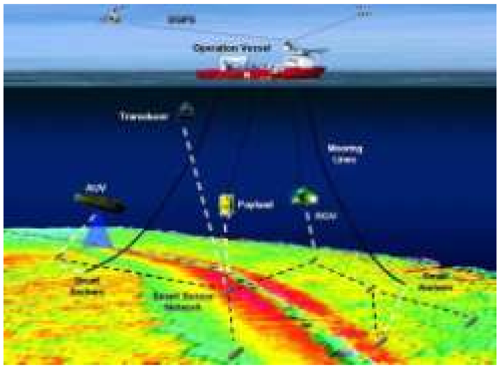

Figure 1.An example application scenario for underwater sensornetworks

LOCALIZATIONSCHEMESSURVEY

Sensor network data is generally interpreted with respect to the spatial location of the sensor nodes. Applications such as event detection, object tracking, and environmental monitoring rely heavily on accurate positional information. However, localization in underwater environments is particularly challenging due to the high attenuation of Radio Frequency (RF) signals, which makes technologies like GPS impractical for underwater use.

To address these challenges, several localization schemes have been proposed, taking into consideration factors such as network topology, hardware limitations, signal propagation characteristics, and energy efficiency. Most of these schemes assume that the positions of a subset of nodes in the network are known in advance. These nodes are commonly referred to as **anchor nodes** or **reference nodes**.Based on the use of positional information, localization techniques can be broadly classified into two categories: **range-based schemes**, which utilize distance or angle (bearing) measurements, and **range-free schemes**, which estimate positions without relying on explicit range or bearing information.

RANGE-BASED SCHEMES

In range-based localization schemes, accurate distance or angle measurements are utilized to estimate the positions of nodes within the network. These schemes depend on range and/or bearing information and typically employ techniques such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), and Received Signal Strength Indicator (RSSI) to determine the relative distances between nodes.In terrestrial sensor networks, localization methods based on ToA or TDoA of acoustic or RF signals include technologies such as UWB-based localization [2], GPS [3], and Cricket [4]. However, in underwater sensor networks, the applicability of such techniques is influenced by the unique characteristics of the underwater environment.Range-based localization schemes in underwater sensor networks can be broadly classified into three categories: infrastructure-based schemes, distributed positioning schemes, and mobile beacon-based schemes. Each of these categories is discussed in detail in the following sections, along with the key challenges associated with their implementation.

Infrastructure-basedschemes

Infrastructure-based localization systems, also known as anchor-based schemes, are conceptually similar to the Global Positioning System (GPS). In such systems, anchor nodes are deployed at known, fixed locations on the seabed. Additionally, surface buoys with known positions (obtained via GPS) can also function as anchor nodes.The position of a sensor node or an Autonomous Underwater Vehicle (AUV) is estimated by measuring its distance from multiple anchor nodes. This is typically achieved by calculating the propagation time of acoustic signals between the node and the anchors. In many scenarios, the number of available range measurements exceeds the number of unknown positional coordinates, resulting in an over-determined system. In such cases, the node's position is estimated using techniques such as the least squares method.One notable example of this approach is the Seaweb system, developed by the U.S. Navy, which has been successfully used for tracking AUVs. Experimental results have demonstrated that Seaweb can achieve a localization accuracy of approximately 7–9 meters within an area of about 3 km × 4 km [5].Another example is the Prospector system, a commercial solution developed by Sonardyne. This system employs four acoustic transponders placed at known locations on the seabed, typically at the corners of a 500 m × 500 m area, supported by surface or subsurface floats. It is capable of tracking divers equipped with transceivers, as well as Remotely Operated Vehicles (ROVs), with high precision across water depths ranging from 5 m to 500 m. According to Sonardyne, the system can achieve an accuracy of up to 300 mm within a 500 m × 500 m grid under shallow water conditions [9].

Distributed Positioning Schemes

Distributed positioning schemes are designed for scenarios where no fixed positioning infrastructure is available, i.e., anchor-free environments. In such schemes, each node communicates only with its one-hop neighbors and estimates distances locally. Based on these local interactions, node positions are determined using multilateration techniques, including atomic, collaborative, and iterative multilateration.

Typically, distributed localization follows three main phases. The first is the distance estimation phase, where nodes measure distances to their neighboring nodes using techniques such as RSSI or Time of Arrival (ToA). The second is the position estimation phase, where nodes compute their coordinates by solving a system of equations, often using a least squares approach. The final stage is the refinement phase, where iterative algorithms are applied to improve the accuracy of the estimated positions.

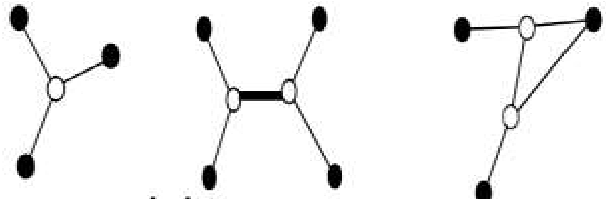

Figure 2. Position uniqueness conditions

Several well-known distributed localization schemes fall under this category, including the N-Hop Multilateration Scheme [6], the Hop-TERRAIN with Refinement Scheme [25], and the Ad Hoc Localization System (AHLoS) and Ad Hoc Positioning System (APS) using Distance Propagation and Euclidean Propagation [26].A key concept in these schemes is position uniqueness, which determines whether a node's position can be uniquely identified based on available distance constraints. The N-Hop Multilateration Scheme [6] outlines the conditions required for unique solutions in one-hop, two-hop, and n-hop scenarios. Initially, nodes estimate their positions using these constraints, and then refinement techniques such as Kalman filtering are applied to enhance accuracy.

In the Hop-TERRAIN scheme [25], initial position estimates are derived using an approach similar to the DV-Hop method. These estimates are then refined using least squares optimization based on locally available information. In contrast, AHLoS and APS [26] employ iterative multilateration, where nodes that successfully estimate their positions act as new reference points (pseudo-anchor nodes). However, a major limitation of this approach is error propagation, as inaccuracies tend to accumulate with increasing hop distance from the original reference nodes.Distance estimation in distributed schemes can be performed using RSSI or ToA measurements. RSSI-based methods are simpler but typically provide lower accuracy, often within a few meters, and are highly sensitive to environmental variations. On the other hand, ToA-based methods offer significantly higher accuracy, often within a few centimeters. In underwater sensor networks, ToA is generally preferred due to the use of acoustic communication, which supports more reliable timing-based measurements.

Most distributed positioning algorithms assume that anchor nodes are randomly distributed across the network and that a relatively high percentage of nodes (typically 5–20%) can act as anchors [6]. While this assumption is reasonable in terrestrial networks where GPS-enabled nodes can serve as anchors, it becomes impractical in underwater environments due to the unavailability of GPS and the difficulty of precisely deploying anchor nodes. Furthermore, even in fully connected networks, not all nodes may be successfully localized. Nodes that do not satisfy the required position uniqueness conditions may fail to compute their positions. As a result, distributed positioning schemes, although flexible and infrastructure-independent, may lead to incomplete localization coverage in practical underwater deployments.

Schemes that use Mobile Beacons/Anchors

Conventional range-based localization techniques typically rely on static anchor nodes with predefined positions. However, more adaptive approaches have emerged that utilize mobile beacons (or anchors) whose positions are dynamically known during operation [8]. In such schemes, a mobile beacon moves across the sensor field while periodically transmitting beacon signals embedded with its current location coordinates. Sensor nodes that receive these signals can estimate their own positions by inferring proximity to the beacon over time.To improve localization accuracy, Received Signal Strength Indicator (RSSI) values from multiple beacon transmissions are often used to estimate distances. As more beacon packets are collected, probabilistic methods—particularly Bayesian inference—are applied to refine the node's position estimate. In terrestrial environments, this process is relatively straightforward, as mobile beacons (such as autonomous vehicles) can rely on GPS for precise positioning.

However, underwater environments introduce a significant complication: the absence of reliable GPS signals. In such cases, the position of the mobile beacon itself—typically an Autonomous Underwater Vehicle (AUV)—must first be determined using alternative localization techniques before it can assist in positioning other nodes.Another limitation arises from the use of RSSI in underwater conditions. Factors such as signal attenuation, multipath propagation, irregular acoustic channels, and environmental noise can lead to high variability in RSSI measurements, reducing reliability. To address this, underwater systems often prefer Time of Arrival (ToA) measurements of acoustic signals, which provide more stable and accurate distance estimation in such environments.A practical implementation of mobile anchor-based localization can be observed in commercial systems developed by Sonardyne [9]. In this approach, a surface vessel equipped with GPS acts as a mobile anchor. The vessel deploys an acoustic transponder into the water, while sensor nodes on the seabed are also fitted with similar transponders. By navigating the vessel over the deployment area, acoustic range and bearing data are collected, allowing precise localization of seabed nodes.

This method has demonstrated strong performance, particularly in shallow water scenarios, achieving localization accuracy within approximately one meter for depths up to 500 meters. Furthermore, the system is scalable and can be deployed in depths ranging from 500 to 7000 meters. Once the positions of seabed nodes are established, they can serve as reference points for localizing other entities such as AUVs, Remotely Operated Vehicles (ROVs), or divers equipped with acoustic transceivers. Additionally, the same acoustic data from the GPS-enabled vessel can be used to track and guide ROVs in real time.In summary, mobile beacon-based localization offers a flexible and scalable solution, particularly in challenging underwater environments. While it overcomes some limitations of static anchor systems, its effectiveness depends heavily on accurate beacon positioning and robust signal processing techniques.

Schemes without Anchor/ Reference Points

Unlike previously discussed approaches, this class of localization techniques operates without any predefined anchor nodes or reference beacons. Instead of depending on externally known positions, these schemes estimate node locations purely based on relative relationships among the nodes themselves, making them particularly attractive in environments where deploying anchors is impractical or too costly.One notable approach, as presented in [28], models the entire sensor network as a system of mathematical constraints. Here, the distances or proximity relationships between neighboring nodes are expressed as a set of equations. A centralized server then processes these constraints using advanced optimization techniques—such as least squares or convex optimization—to derive the most probable spatial configuration of all nodes. In essence, the network "self-organizes" into a geometric layout that best satisfies the observed inter-node relationships.

Another significant contribution is the infrastructure-less, GPS-free localization algorithm proposed by Capkun et al. in [29]. This method eliminates reliance on any external positioning system by enabling nodes to collaboratively determine their relative positions. Nodes exchange local distance information with their neighbors and iteratively refine their estimates, eventually forming a consistent coordinate system for the entire network.While anchor-free schemes offer clear advantages in terms of deployment flexibility and cost efficiency, they are not without limitations. Since no absolute reference exists, the resulting node positions are often determined up to a rotation, translation, or reflection, meaning the network map may be accurate in shape but not aligned to real-world coordinates. Additionally, these methods can be computationally intensive and sensitive to measurement errors, especially in large-scale or noisy environments.Despite these challenges, anchor-free localization remains a powerful concept, particularly in scenarios where traditional infrastructure is unavailable. It reflects a shift toward more self-reliant and adaptive network design, where the system derives structure from within rather than relying on external guidance.

Problems and Challenges

Localization in underwater wireless sensor networks (UWSNs) is not just a technical problem—it's a battle against physics, environment, and hardware limitations all at once.A major challenge arises in schemes based on Time of Arrival (ToA) or Time Difference of Arrival (TDoA). These techniques demand precise time synchronization between transmitting and receiving nodes. In terrestrial networks, this is often handled using radio frequency (RF) signals. For example, Savvides et al. [20] and Kwon et al. [21] exploit the significant difference in propagation speeds between RF and acoustic signals to estimate distance. However, this approach breaks down underwater because RF signals attenuate rapidly and are practically unusable. As a result, underwater systems must rely on specialized synchronization protocols, such as those proposed by Syed et al. [10], which are inherently more complex and sensitive to delay.

Another critical factor is propagation latency. Acoustic signals travel much slower than RF signals, meaning even small timing errors can lead to large localization inaccuracies. To mitigate this, advanced signal processing and statistical filtering techniques [22] are often employed to refine ToA and TDoA estimates.Adding another layer of complexity, many localization models assume a constant speed of sound (typically 1500 m/s). In reality, this assumption is an oversimplification. The speed of sound underwater varies with temperature, salinity, and depth [11]. Ignoring these variations can introduce significant errors, whereas models that adapt to environmental conditions tend to achieve better accuracy [7].

When it comes to RSSI-based localization, the underwater environment becomes even more unpredictable. Acoustic signals are affected by multipath propagation, caused by reflections from the sea surface and seabed, as well as scattering effects. The behavior of the sea surface itself is dynamic—it may act as a reflector or scatterer depending on wave activity and wind conditions [23]. Similarly, the seabed contributes additional reflections, further complicating signal interpretation. Studies such as [24] suggest that these multipath effects can often be modeled using Rayleigh fading, particularly in shallow waters.Beyond multipath issues, acoustic signals also suffer from attenuation, geometric spreading losses (spherical or cylindrical), and absorption due to environmental factors like air bubbles. External noise sources—such as marine life (e.g., shrimp noise)—introduce further interference [23]. These combined effects result in high variability in RSSI measurements, making them less reliable for accurate ranging. Consequently, ToA and TDoA techniques are generally preferred in underwater environments despite their synchronization challenges.

Finally, Angle of Arrival (AoA)-based schemes, which are effective in terrestrial networks, face practical limitations underwater. These methods require specialized antenna or sensor array configurations to measure signal direction, which increases hardware complexity and cost. Moreover, AoA-based localization involves solving non-linear equations, adding computational overhead [12]. For resource-constrained underwater sensor nodes, such requirements can be difficult to meet.In summary, underwater localization is shaped by a harsh and variable environment where timing precision, signal distortion, environmental dynamics, and hardware constraints all intersect. Any robust solution must navigate these challenges carefully, balancing accuracy with feasibility.

RANGE-FREE SCHEMES:

Range-free localization schemes estimate node positions without relying on explicit distance or angle measurements. Unlike range-based approaches, these methods do not utilize techniques such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), or Angle of Arrival (AoA) to compute inter-node distances. Instead, they infer location information using network connectivity and hop-based information.Common examples of range-free techniques include the centroid algorithm, DV-Hop, and Density-Aware Hop Count Localization

(DHL). One of the key advantages of these methods is their simplicity and low hardware requirements, as sensor nodes are not required to perform complex signal measurements such as RSSI, ToA, or AoA. This makes them highly suitable for resource-constrained wireless sensor networks. In practice, algorithms like DV-Hop and DHL have been effectively implemented on standard sensor platforms such as Crossbow MICAZ motes.However, this simplicity comes at the cost of accuracy. Range-free schemes generally provide only a coarse estimation of node positions compared to range-based techniques. Based on their operational principles, range-free localization methods can be broadly categorized into two types: hop-count-based schemes and area-based schemes.

Hopcount based Schemes

In this section, hopcount-based localization approaches are discussed, particularly in scenarios where anchor nodes are positioned along the boundaries or at the corners of a square deployment region. These methods rely on network connectivity rather than direct distance measurements, making them suitable for low-cost sensor networks.One of the most widely used techniques in this category is the Distance Vector-Hop (DV-Hop) algorithm. This method begins with a distance vector exchange process, allowing each node in the network to determine its minimum hop count to multiple anchor nodes. During this phase, nodes maintain routing tables and communicate only with their immediate neighbors, ensuring scalability and reduced communication overhead.Once anchor nodes obtain hop-count distances to other anchors, they estimate the average physical distance per hop. This average hop distance is then broadcast across the network as a correction factor. Using this information, unknown nodes convert their hop counts into approximate physical distances, which are further utilized for position estimation through triangulation.

While DV-Hop is simple and effective, its performance is highly dependent on network conditions. It tends to produce accurate results in networks where nodes are uniformly distributed and densely deployed. However, in real-world environments where node distribution is often irregular or sparse, its accuracy degrades.To address this limitation, improved methods such as Density-Aware Hop-count Localization (DHL) have been introduced. DHL enhances localization accuracy by incorporating local node density into the calculation of average hop distance. Additionally, it accounts for the cumulative nature of distance estimation errors, which tend to increase as the hop path length grows. This makes DHL more suitable for practical deployments with non-uniform node distributions.Another important concept in hopcount-based schemes is iterative multilateration, where nodes that have already estimated their positions act as new anchor nodes in subsequent iterations. However, this approach must be applied carefully, as errors can propagate through the network. For instance, in a square grid deployment, it has been observed that localization errors are typically higher near the boundaries and lower toward the center.

To mitigate this issue, the Selective Iterative Multilateration (SIM) algorithm has been proposed. Instead of promoting all localized nodes to anchors, SIM selectively chooses only those nodes whose estimated positions meet a certain accuracy threshold. This controlled selection helps limit error propagation and improves overall localization performance.In summary, hopcount-based schemes offer a practical and energy-efficient solution for localization in wireless sensor networks. However, their accuracy depends heavily on network topology, node distribution, and the careful handling of iterative processes.

Centroid Scheme

The centroid localization scheme is one of the simplest range-free approaches used in wireless sensor networks. In this method, anchor (reference) nodes are deployed in a structured manner, typically forming a rectangular or grid-like topology across the sensing region. Each anchor node periodically broadcasts beacon messages containing its positional coordinates.A sensor node estimates its position based on the set of anchor nodes from which it successfully receives beacon signals. Instead of calculating exact distances, the node assumes that it lies within the coverage region of these anchors. The estimated position is then computed as the geometric centroid (average) of the coordinates of all such neighboring anchor nodes.This scheme is attractive due to its low computational complexity and minimal hardware requirements, as it does not rely on additional ranging techniques such as Time of Arrival (ToA) or Angle of Arrival (AoA). However, its accuracy is highly dependent on the density and distribution of anchor nodes. A higher concentration of anchors generally leads to improved localization performance.Despite its simplicity, the centroid scheme faces practical challenges in certain environments. For instance, in underwater sensor networks, deploying anchor nodes in a well-defined rectangular mesh on the seabed is often impractical due to environmental constraints, mobility of nodes, and high deployment costs. Consequently, the applicability of this approach in such scenarios remains limited.

Area Localization Scheme (ALS)

The Area Localization Scheme (ALS) [16] is a centralized, range-free localization approach that estimates the position of a sensor node within a bounded region rather than determining its exact coordinates. This method is particularly suitable for large-scale wireless sensor networks where simplicity and energy efficiency are prioritized over high-precision localization.In ALS, anchor nodes periodically transmit beacon signals at multiple discrete power levels. Each power level corresponds to a specific transmission range, effectively partitioning the deployment area into several smaller regions. Sensor nodes detect these beacon signals and identify the minimum power level received from each anchor node. This information is then forwarded to a central processing unit (sink), where localization is performed.

The collected data is represented as an n-dimensional signal coordinate, where each dimension corresponds to an anchor node, and the value indicates the lowest received power level from that anchor. This coordinate uniquely characterizes the region in which the sensor node is located.To illustrate, consider a square sensing field with four anchor nodes positioned at its corners. Each anchor transmits beacon signals at three distinct power levels, labeled from 1 (lowest) to 3 (highest). The transmission ranges corresponding to these power levels divide the area into multiple subregions using contour boundaries. For example, contour lines associated with power levels 1 and 2 define progressively larger coverage areas, while the highest power level extends beyond the entire region.A sensor node located within a specific subregion determines the minimum power level received from each anchor. For instance, if a node receives signals at power level 3 from three anchors and at power level 2 from the fourth anchor, its signal coordinate can be represented as ⟨3, 3, 3, 2⟩. This coordinate uniquely maps the node to a particular region within the sensing field, as illustrated in Fig. 3.

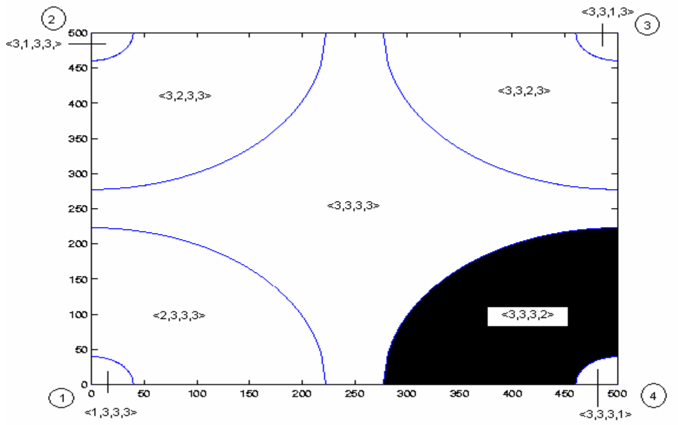

Figure 3. Example of ALS, where the shaded region corresponds to the signal coordinate ⟨3, 3, 3, 2⟩.

The final localization is performed at the sink, which maps the signal coordinate to a predefined region in the deployment area. The accuracy of ALS depends on the granularity of these regions, which can be controlled by adjusting the number of transmission power levels. Increasing the number of power levels results in finer partitions and improved localization resolution, albeit at the cost of increased communication overhead.

Approximate Point In Triangle (APIT)

The Approximate Point in Triangle (APIT) algorithm is a widely used range-free localization technique designed for wireless sensor networks. In this approach, an unknown node selects groups of three anchor nodes from the set of anchors within its communication range (i.e., audible anchors). These three anchors form a triangular region, and the node evaluates whether it lies inside or outside this triangle.In theory, this determination can be performed using the Point-In-Triangle (PIT) test, which provides an exact geometric solution. However, the PIT test assumes ideal conditions, such as node mobility and precise measurements, which are rarely achievable in real-world deployments. Consequently, implementing PIT directly in static and resource-constrained sensor networks becomes impractical.To address these limitations, the APIT test was introduced as an approximation method [17]. Instead of relying on precise geometric calculations, APIT leverages variations in Received Signal Strength Indicator (RSSI) values from neighboring nodes. By comparing RSSI readings, a node infers whether it is likely located inside or outside a given triangular region without requiring physical movement.

This process is repeated for multiple combinations of audible anchor nodes, generating a set of triangular regions. By intersecting all regions where the node is determined to be inside, the algorithm progressively refines the estimated location area. Finally, a centralized processing unit or sink node aggregates this information to compute a more accurate approximation of the node's position.Overall, APIT offers a practical balance between accuracy and computational simplicity, making it suitable for large-scale sensor networks where precise distance measurements are not feasible.

Challenges of range-free schemes

Range-free localization techniques have gained significant attention due to their simplicity and low hardware requirements. However, despite these advantages, several challenges limit their performance and applicability in real-world wireless sensor network (WSN) deployments.

A. Limited Localization Accuracy

One of the primary drawbacks of range-free schemes is their relatively low accuracy compared to range-based methods. Since these techniques rely on connectivity information rather than precise distance or angle measurements, the estimated node positions often represent coarse approximations. This limitation becomes more pronounced in applications where fine-grained localization is critical.

B. Sensitivity to Node Density

The performance of range-free algorithms is highly dependent on node density. In sparse networks, nodes may have fewer neighboring anchors, leading to insufficient information for accurate localization. Conversely, in very dense networks, excessive connectivity may introduce ambiguity, making it difficult to distinguish between possible locations.

C. Anchor Node Dependency

Range-free schemes heavily rely on anchor nodes (nodes with known positions) for localization. The number and placement of these anchors significantly influence the accuracy of the estimated positions. Poor anchor distribution or an insufficient number of anchors can lead to large localization errors and uneven coverage across the network.

D. Error Propagation

In multi-hop based range-free schemes, such as DV-Hop, localization errors can accumulate as information propagates through the network. Small inaccuracies at intermediate nodes may amplify over multiple hops, resulting in substantial deviations in the final position estimates.

E. Environmental and Signal Variations

Although range-free methods do not explicitly use distance measurements, they may still depend on signal characteristics such as connectivity or RSSI. Environmental factors, including obstacles, interference, and irregular radio propagation, can affect signal behavior and lead to incorrect assumptions about node proximity.

F. Scalability Issues

While range-free schemes are generally considered scalable, their performance may degrade in very large networks. Increased network size can lead to higher communication overhead, longer convergence times, and greater uncertainty in localization results, particularly in distributed implementations.

G. Limited Applicability in High-Precision Systems

Range-free localization is not suitable for applications requiring high positional accuracy, such as robotic navigation or precision tracking. However, in many practical scenarios—such as environmental monitoring or geographical routing protocols [18]—a coarse estimate of node location is sufficient for effective operation.

H. Trade-off Between Cost and Performance

Range-free schemes are attractive due to their low cost and minimal hardware requirements, especially in terrestrial sensor networks where nodes may not support advanced ranging technologies. Although underwater sensor networks can utilize acoustic signals for more accurate ranging, this often increases system complexity and energy consumption. As a result, range-free approaches continue to be preferred in cost-sensitive and large-scale deployments where approximate localization is acceptable.

SIGNAL PROCESSING/PROBABILISTIC SCHEMES

The third category of localization techniques in wireless sensor networks involves the use of signal processing methods and probabilistic approaches. Unlike traditional range-based or range-free schemes, these techniques exploit detailed characteristics of the received signals to estimate node positions.A well-known example of this approach is the fingerprinting method developed by the U.S. Wireless Corporation [19]. Rather than relying on parameters such as signal strength or propagation time, this method utilizes the structural properties of received signals, including multipath patterns and other unique signal features present at a specific location.In this technique, each physical location is associated with a distinct “signal signature” or fingerprint. These fingerprints are generated during an offline training phase, where signal data is collected across the deployment area—often by systematically moving a receiver (e.g., mounted on a vehicle) and recording signal characteristics at various points. The collected data is then stored in a centralized database.

During the localization phase, a node measures the current signal characteristics and compares them against the stored fingerprints. By identifying the closest match, the system can estimate the node’s location with relatively high accuracy, even in complex environments where traditional methods may struggle.Despite its advantages, this approach presents several practical challenges. The creation of the fingerprint database requires significant time, effort, and resources, particularly in large or dynamic environments. Furthermore, any changes in the environment—such as obstacles, signal interference, or infrastructure modifications—can alter signal patterns, thereby reducing the accuracy of the stored fingerprints. As a result, frequent updates to the database may be necessary.Due to these limitations, signal processing and probabilistic schemes are generally not well-suited for ad hoc or rapidly deployed sensor networks, where pre-collection of signal data is impractical. However, they remain effective in controlled or semi-static environments where high localization accuracy is required and infrastructure support is available.

COMPARISON OF LOCALIZATION SCHEMES

Table 1 compares the different localization schemes that have been discussed in this paper. Infrastructure-based positioning systems are suitable for shallow water applications as anchor nodes can be placed on the seabed at known locations.

Schemes	Range basedor Range Free	Accuracy	Distributedor Centralized	Placement ofanchornodes	% of anchornodes	AdditionalComments
Infrastructure basedpositioningsystems	Range based,ToA,TDoA	Accurate: 1 to10 mfor 3 km × 4 kmarea. Accuracydependsonarea size	Distributed	At the cornersof a squaregrid	Small	Requires placement ofanchor nodesonsea-bed
Distributedpositioning	Range based,ToA,TDoA	NotAccurate: 0.5*(Radio Range)to1*(RadioRange)	Distributed	Distributedrandomly	High(5%to 20% ofnodes)	Requires placement ofanchor nodesonsea-bed
MobileBeacons	Range based,ToA	Accurate: < 1 m,forshallowwaterof< 500 m (Sonardyne)	Distributed	Only oneanchor	Low	Themobilebeaconcouldbe a ship equipped withGPS, oranAUV /ROV whoselocationisknown
DV-Hop	RangeFree	Not Accurate:0.5	Distributed	Atthecorners of a	Low	Simpletoimplement

		(RadioRange) to1(RadioRange)		squaregrid		
Centroid basedlocalization	RangeFree	NotAccurate: 0.5*(Radio Range)to1*(RadioRange)	Distributed	In a gridstructure	High (Highforgood performance)	Simpletoimplement ,butrequiresplacementof anchorsinasquaremesh
ALS	RangeFree	Not Accurate:0.5 *(Radio Range)to1*(RadioRange)	Centralized	At the cornersof a squaregrid	Low	Anchornodesmustbeableto cover area inconsideration.Simple to implement
APIT	RangeFree	Not Accurate:0.5 *(Radio Range)to1*(RadioRange)	Distributed orCentralized	Randomlydistributed	High (Highforgoodperformance)	Anchornodesmustbeableto cover area inconsideration.Simple to implement
Fingerprinting, SignalProcessingbased	Range based,RSSI	Accurate, but onlygoodforsmallareas	Centralized			

Alternatively, the position of the anchor nodes on the seabed can be calibrated using a mobile ship equipped with GPS (mobile beacon scheme). The anchor nodes on the seabed can then help position AUVs, ROVs, and other nodes in the system. Positioning can be done with a high level of accuracy with any of the range-based schemes described above, if a sufficient number of anchor nodes are placed on the seabed.The problem is a lot more challenging for deep sea applications because it is difficult to deploy a lot of anchor nodes in precise locations. One solution for deep water applications would be to suspend a ROV deep into the sea, position the ROV with respect to the ship, and then use the ROV to position the sensor nodes on the seabed. Error propagation would be a problem with such a solution, as the error in the location of the ROV would be propagated to the UWSN.Schemes that require a small percentage of anchor nodes would be useful in deep water applications. If the precise locations of the nodes are not required, range-free schemes like ALS or DHL could be used. For example, if the location of the nodes is to be estimated only for routing data efficiently from the sensors to the sink, range-free schemes could be used.

Localization For Uwsns In Offshore Engineering

Accurate localization remains one of the most critical—and difficult—problems in underwater construction and offshore engineering. Unlike controlled terrestrial environments, the underwater domain is unpredictable, dynamic, and often unforgiving.The challenge becomes even more pronounced as offshore operations move toward deeper waters. In such environments, the seabed (mudline) does not remain stable; instead, it continuously shifts due to currents, sediment movement, and geological activity. This ever-changing configuration makes it extremely difficult to rely on fixed reference points or pre-deployed infrastructure.Moreover, deep-sea environments are typically unstructured and poorly mapped. Traditional localization methods that depend on stable anchor nodes or pre-defined coordinates struggle to maintain accuracy under these conditions. Even minor positional errors can propagate through the network, leading to significant inaccuracies in monitoring, navigation, or construction tasks.

For offshore engineering applications—such as pipeline installation, subsea structure placement, and inspection using Autonomous Underwater Vehicles (AUVs) or Remotely Operated Vehicles (ROVs)—precise localization is not just beneficial, it is essential. Any deviation can lead to operational inefficiencies, increased costs, or even safety risks.
As a result, there is a growing need for adaptive and robust localization techniques that can function reliably in deep, dynamic, and uncertain underwater environments. Solutions must balance accuracy with practicality, often leveraging hybrid approaches that combine limited infrastructure with mobile or cooperative localization strategies.

DEEP WATER INSTALLATION

Subsea infrastructure, including templates (Fig. 4), Christmas trees, and manifolds, must be installed with a high level of positional and directional accuracy to ensure reliable operation and compatibility with existing systems. These structures are required to be placed at predefined spatial coordinates and aligned with specific compass headings, while maintaining strict tolerances in rotational, vertical, and lateral dimensions.For typical deepwater installations, acceptable tolerances are within 25 cm of the intended location and within 2.5° of the specified orientation for large subsea templates. In comparison, the installation of manifolds into pre-positioned templates demands even greater precision, as small misalignments can significantly affect structural integration and operational performance. Consequently, the Underwater Wireless Sensor Network (UWSN) must provide high-resolution localization data to support accurate placement, particularly in environments where installations occur in close proximity to other subsea equipment.

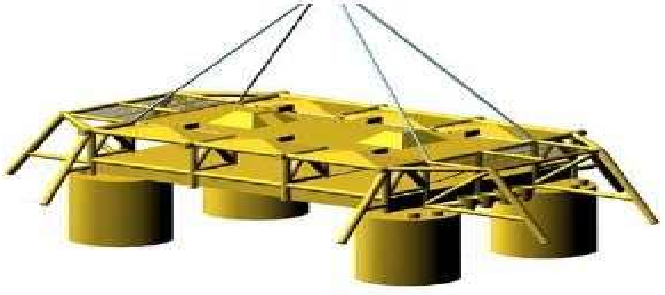

Figure 4. A subsea template

In practice, positioning data obtained from the UWSN can be transmitted in real time to intelligent crane hook systems or remotely operated vehicle (ROV) operators, enabling active and fine-grained control of payload placement. Alternatively, this information may be relayed to the installation vessel's bridge to assist in overall maneuvering and alignment during deployment.Given the substantial operational costs associated with crane barges and supporting marine spreads, installation activities are typically carried out within limited weather windows. Under such constraints, the acoustic positioning system is expected to deliver highly reliable performance throughout the operation, as any failure or inaccuracy can lead to significant delays and increased costs.

Metrology:-

Metrological measurements are conducted following the installation of subsea structures on the seabed to determine the relative distances and spatial relationships between adjacent templates and other subsea components. These measurements are critical for ensuring the precise fabrication and alignment of connecting spool pieces, which link different structures within the subsea system. An Underwater Wireless Sensor Network (UWSN) capable of delivering high-precision positioning during installation can be effectively repurposed for metrology applications. By utilizing the same system for both installation and post-installation measurements, the overall construction workflow can be significantly streamlined. This integrated approach minimizes the reliance on separate metrology operations, thereby reducing project timelines and associated costs while maintaining the required level of accuracy.

Reliability Monitoring of Mooring System:

A variety of mooring configurations are widely used in offshore operations to maintain the station-keeping of Floating Production Storage and Offloading (FPSO) units and other drilling or production vessels. Accurate knowledge of anchor positions plays a crucial role in predicting and analyzing the dynamic response of these systems, including Turret Mooring, Single Point Mooring, and Spread Mooring configurations. In deepwater environments, Vertically Loaded Anchors (VLAs) are commonly deployed due to their high holding efficiency. These anchors are typically installed with a long mooring scope and are designed to operate within an uplift angle limit of approximately 15° at the seabed. Beyond the point of maximum holding capacity, additional loading may cause the anchor to gradually lose resistance and be pulled toward the seabed surface, resulting in reduced holding performance. While conventional mooring systems already provide basic positioning capabilities for FPSO units, integrating Underwater Wireless Sensor Networks (UWSNs) offers a promising enhancement. By incorporating real-time feedback on anchor positioning and seabed soil conditions, UWSNs can significantly improve system reliability, support informed decision-making, and contribute to reduced operational costs.

Conclusions :-

Localization in terrestrial sensor networks has been extensively explored and is relatively well understood. In contrast, localization in Underwater Wireless Sensor Networks (UWSNs) introduces unique challenges, primarily due to the reliance on acoustic communication, which is affected by factors such as signal attenuation, multipath propagation, and variable sound speed in water. This paper has presented a comprehensive overview of localization techniques applicable to UWSNs, broadly categorizing them into range-based and range-free approaches. A comparative discussion of these methods highlights their respective strengths and limitations in terms of accuracy, complexity, and feasibility in underwater environments. Although many of the reviewed techniques demonstrate promising results in simulation studies, their practical effectiveness in real-world underwater conditions remains an important area for further investigation. Experimental validation and field deployment are necessary to assess their robustness and adaptability. Furthermore, the role of localization in offshore engineering applications has been emphasized, where accurate positioning is essential for tasks such as subsea installation, metrology, and mooring system monitoring. Advancements in localization technologies are therefore expected to play a key role in improving the reliability, efficiency, and safety of UWSN-based offshore operations

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