Localization with Dive'N'Rise (DNR) Beacons for Underwater Acoustic Sensor Networks

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ABSTRACT

In this paper, we address the localization issue in Underwater Sensor Networks (UWSNs). We propose Dive'N'Rise(DNR) Positioning, the novel idea of using DNR beacons for localization. These beacons get their coordinates from GPS while floating above the water, then they dive into water. While sinking and rising, they broadcast their positions. Sensor nodes are localized by passively listening to DNR beacon messages which reduces the communication cost and the energy consumption. We analyze localization success and error for static and mobile UWSNs.

Categories and Subject Descriptors: C.2.1 [Computer Communication Networks]: Network Architecture and Design, C.3 [Special-Purpose And Application-Based Systems]: Underwater acoustic sensor networks - localization

General Terms: Performance

Keywords: Underwater sensor networks, localization, positioning, mobile beacon

1. INTRODUCTION

Pollution monitoring, harbor surveillance, undersea archeology, ocean bottom seismic research, ocean life observation are among some of the fields to benefit from the wide opportunities that Underwater Sensor Networks (UWSNs) offer. Nevertheless, before UWSNs become commercially available or widely used, there are certain issues to be addressed [1–4]. Localization is one of the major and challenging tasks in UWSNs. It is important because raw sensor data without spatio-temporal tagging does not provide much information. It is challenging because GPS signal does not propagate through water and alternative cooperative positioning schemes are not applicable in practice due to acoustic channel properties. Acoustic channel have low bandwidth, high propagation delay and high bit error rate. The speed of sound is approximately 1500 m/s, yet it varies with temperature, pressure and salinity [3]. Another challenge is the mobility. Moreover, energy limitation is still an issue as it is in other sensor networks.

Localization is widely studied for terrestrial sensor networks. For UWSNs, there are only a few proposals [5–7]. In [6], a hierarchical deployment that includes surface buoys and two types of underwater nodes: anchor nodes and ordinary sensor nodes, is studied. At first, anchor nodes are localized by the help of surface buoys and then the ordinary sensors are localized using the coordinates of these anchor nodes. Anchor nodes are spread among sensors to help localization for large-scale mobile UWSNs. Here, the localization of anchor nodes is more challenging and it is not considered in detail. In [7], the authors propose an anchor-free localization method for UWSNs. This scheme requires a node discovery phase before localization which includes high message exchange.

In this paper, we introduce a new localization scheme, DNR-Positioning, that works in large-scale networks, 3-D space, establishes minimal message exchange and considers mobility. We propose to use DNR beacons which are low-cost, mobile nodes that can sink down with the weight force and can bubble up with a bladder. They learn their coordinates via GPS before sinking and distribute this information as they are diving. The sensor nodes receive messages from DNR beacons and estimate their coordinates using either bounding box or triangulation algorithms [8]. We consider two scenarios with: static and free drifting nodes. We study the performance of DNR-Positioning in terms of the number of successfully localized nodes and the localization error.

2. DNR-POSITIONING

The tradeoff between message overhead and the cost of using large number of anchors can be solved by using few, inexpensive, mobile beacons. We consider simple apparatuses that can dive with the help of extra weight. When they reach a certain depth, the weight is released and they rise/emerge with the help of a bladder.

DNR beacon is responsible for getting its GPS coordinates when floating above the water. Then, while diving it broadcasts its coordinates. We assume the sensor nodes are equipped with pressure sensors. Hence, they know their depth (z coordinate) and estimating the x-y coordinates is sufficient to determine their location. Also, DNR beacons are able to maintain the value of the z coordinate via pressure sensors.

Sensor nodes listen to broadcast messages from DNR beacons. Range measurement is done by using the time of arrival of these messages. We assume the nodes are synchronized. After hearing from several beacons, sensor nodes can estimate their coordinates.

3. MOBILITY WITH CURRENTS

In this paper, we consider static and mobile UWSNs. In static case, we assume there are no currents and the sensor nodes do not move. The DNR beacons sink following a straight path. In mobile case, we consider motion with the force of slow currents. Both sensor nodes and DNR beacons drift with the effect of currents. We

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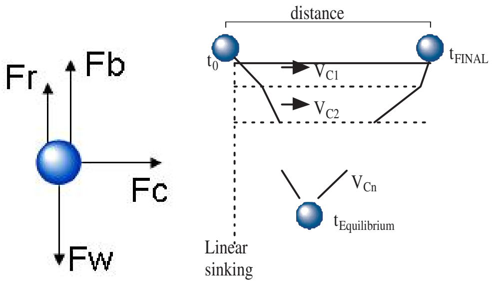

Figure 1: (a)Forces acting on a sinking object (b)Rising and Sinking trajectory.

assume a simple mobility model since this is a preliminary investigation of the interaction between mobility and DNR-positioning.

3.1 Motion of Sinking DNR Beacons

The motion of a sinking beacon obeys:

$$\sum \vec{F} = m.\vec{a} \tag{1}$$

The acceleration $\vec{a}$ is determined by the sum of forces $\vec{F}$ acting on object of mass m. The mass of an object is given by $m = \rho.V$, where ρ is the object's density and V is the volume.

The forces involved in underwater motion are described in Figure 3.1. Here, $\vec{F_w}$ is the weight force. $\vec{F_b}$ is the buoyant force. $\vec{F_r}$ if the fluid resistance force and depends on the object shape. Finally, $\vec{F_c}$ is the current force. The equations for the forces are given as [9]:

$$\vec{F_w} = \rho.V.\vec{g} \tag{2}$$

$$\vec{F_b} = -\rho_{fluid}.V.\vec{g} \tag{3}$$

$$\vec{F_r} = -K.\rho_{fluid}.\mu.A_{fluid}.\vec{v} \tag{4}$$

$$\vec{F_c} = C\sigma.A_c.(\vec{v_c} - \vec{v}) \tag{5}$$

Here, $\vec{g}$ is the gravity, ρ_{fluid} is the density of water, K and C are constants. The cross sections of the object subject to resistance and current are A_{fluid} and A_c, respectively. The velocity of the object is $\vec{v}$ and the velocity of the current is $\vec{v_c}$. Finally, μ and σ are the parameters related with the shape of the object.

As described by [9], we obtain the dynamic system parametric equations. The position (x, y, z) at time t for an object with initial position $(x(t_0), y(t_0), z(t_0))$ and initial velocity $(v_x(t_0), v_y(t_0), v_z(t_0))$ is given by:

$$x(t) = x(t_0) + v_{cx}.(t - t_0) + \frac{v_x(t_0) - v_{cx}}{C\sigma.A_{xy}/\rho.V}.[1 - e^{-\frac{C\sigma A^{xy}}{\rho V}(t-t_0)}] \tag{6}$$

$$y(t) = y(t_0) + v_{cy}.(t - t_0) + \frac{v_y(t_0) - v_{cy}}{C\sigma.A_{xy}/\rho.V}.[1 - e^{-\frac{C\sigma A^{xy}}{\rho V}(t-t_0)}] \tag{7}$$

$$z(t) = v_{z_{term}}.(t - t_0) + [v_{cy} - v_{z_{term}}].[1 - e^{-\frac{K.\rho_{fluid}.\mu A^z}{\rho V}(t-t_0)}] \tag{8}$$

where v_{cx}, v_{cy} are the speed of the current in x and y, direction and $v_{z_{term}}$ is the terminal velocity when the sinking object reaches the desired depth.

3.2 Motion of Sensor Nodes

Sensor nodes are assumed to be effected by the same current force ($\vec{F_c}$) as DNR beacons. They drift in the same direction as DNR beacons. However, they are able to maintain their depth. The currents were modeled such that their x and y coordinates change in the following way:

$$x(t) = x(t-1) + v_{cx} \tag{9}$$

$$y(t) = y(t-1) + d_t.v_{cy} \tag{10}$$

where d_t specifies the direction:

$$d_t = \begin{cases} -1 & \text{if } d(t-1) = 1 \text{ and } y(t-1) > l_{cy} \\ 1 & \text{if } d(t-1) = -1 \text{ and } y(t-1) < -l_{cy} \end{cases}$$

We assume the main current is along the x-axis, with constant speed v_{cx} randomly chosen from $[0, v_{max}]$. On the y-axis, the nodes are allowed to oscillate in relatively small amounts (l_{cy}). They mimic a zigzag motion heading for a specific direction.

4. SIMULATION RESULTS

We implement DNR-Positioning in Qualnet [10] simulator. The sensor nodes are randomly deployed in a 1km x 1km x 1km volume in 3D space. The number of sensor nodes varies from 100 to 500. We use 25 DNR beacons which are randomly deployed on the surface. The simulation time is set to 1000S and DNR beacons send messages at 1S, 5S and 10S intervals. The nodes have a communication range of 250m and the data rate is 50 kbit/s [11]. We use acoustic medium for physical layer, two-ray path loss model and CSMA for medium access.

We used two schemes for evaluating localization: bounding box and triangulation. Bounding box method draws a rectangular region with the distance estimates to beacons. The intersection of the diagonals gives the coordinates of the node.

Our performance metrics are the number of localized nodes and the ratio of mean error to terrain size. We first evaluate the results for static sensor nodes and then mobile scenarios. Static case, where there are no currents, gives us the boundaries of the localization scheme while the mobile case provides insights to real world implementations. Our mobility model is a preliminary one and it is oversimplified when the complexity of the ocean currents near the surface are considered.

4.1 DNR-Positioning without Currents

In this set of simulations the sensor nodes are assumed to be static and the DNR beacons sink following a straight path. This a case where there are no currents and nodes do not drift. In our scheme, the communication cost and the energy consumption depend on simulation time, frequency of location updates (interval) and number of beacons. The sensor nodes are passive and they spend energy only in receiving and processing a message which is low compared to transmission energy. Hence, we only use localization success and error as performance metrics.

Localization success, i.e. the ratio of localized nodes are studied under two different localization techniques; bounding box and triangulation. In Figure 2, we give the localization success for bounding box method. Bounding box localizes 70-80% of the nodes, whereas, in Figure 3, triangulation achieves to localize 100% of the nodes. The performance of bounding box is highly dependent on anchor positions, i.e. a node is better localized if the beacons are sent from opposite corners of the box. Triangulation gives better

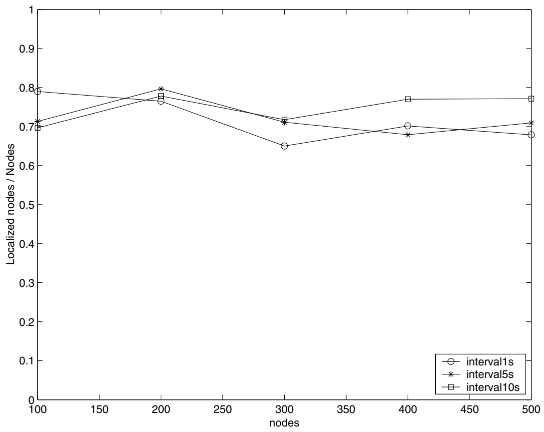

Figure 2: Ratio of localized nodes in static scenario with bounding box.

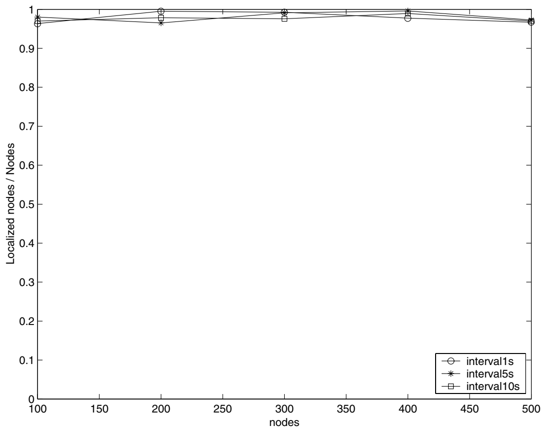

Figure 3: Ratio of localized nodes in static scenario with triangulation.

results for the ratio of mean error, as well, as seen from Figures 4 and 5.

4.2 DNR-Positioning with Currents

Here, we evaluate the performance of DNR-Positioning when the nodes move with the currents. We assume sensor nodes move with a maximum speed v_{max} of 25cm/s [12]. The maximum displacement in y coordinate is set to 5m so that nodes can follow the current in x coordinate and as well have an oscillation.

In Figure 6 and Figure 7 we show the number of localized nodes for bounding box and triangulation, respectively. For bounding box, the localized nodes ratio is around 70-80%. This result is close to the static case, where triangulation behaves similar and gives 100% localization. Ratio of mean error, given in Figure 8 and 9, is similar to the static case, as well.

The mobility model causes the whole network shift in one direction with small random displacements. Therefore, the results with currents is similar to static scenarios. While this model may hold for deep waters and the 25cm/s is reasonable for such cases, thinking that DNR beacons have to surface, it is evident that the results

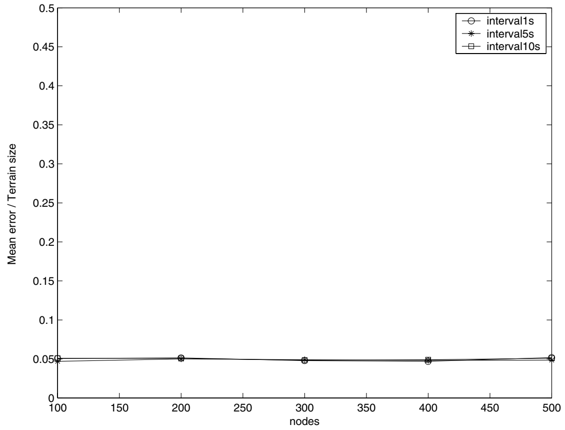

Figure 4: Ratio of error in static scenario with bounding box.

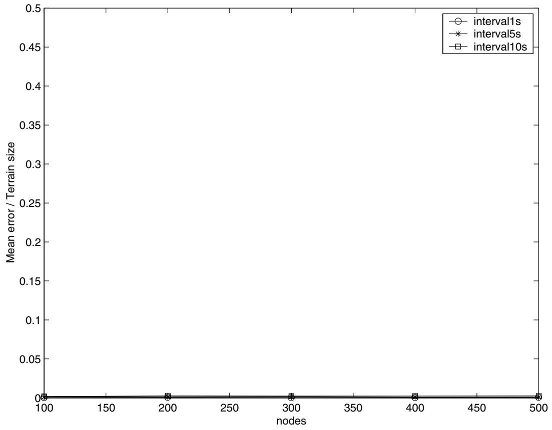

Figure 5: Ratio of error in static scenario with triangulation.

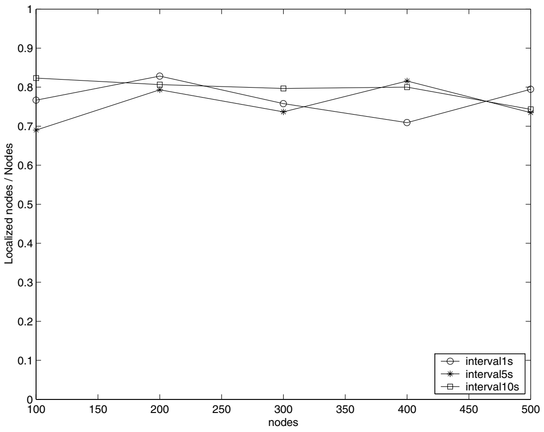

Figure 6: Ratio of localized nodes in mobile scenario with bounding box.

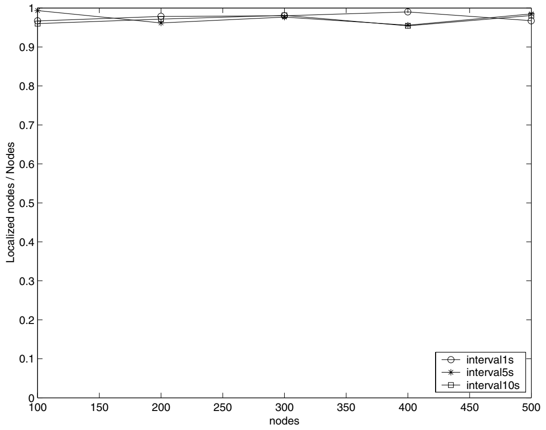

Figure 7: Ratio of localized nodes in mobile scenario with triangulation.

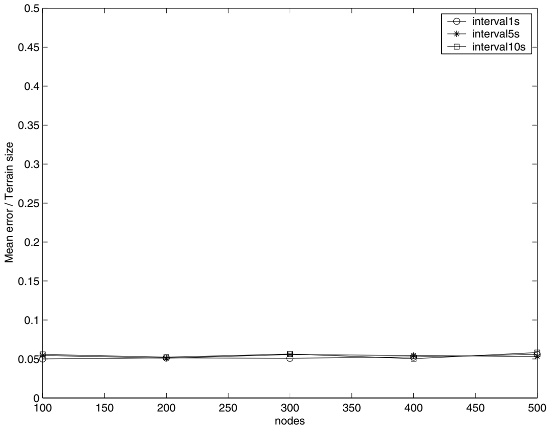

Figure 8: Ratio of error in mobile scenario with bounding box.

would be different with a more realistic mobility model. As a future work, we intend to integrate a realistic shallow water model with a deep water model and investigate the performance of DNR-Positioning.

5. CONCLUSION

DNR-Positioning is able to solve the localization problem in underwater sensor networks without any expensive hardware. It can localize 100% nodes with small error. Moreover, no message exchange is required. Sensor nodes are able to learn their coordinates just by listening. This passive learning results in saving energy and reducing communication cost. DNR beacons can readily work with MAC protocols that assume sleep/wakeup cycles. In addition, the performance can be improved by simply adding message exchange among neighbor sensor nodes after waking up.

Some of the assumptions we make about mobility are only valid for deep waters. However, DNR beacons need to surface to get GPS coordinates and they are subject to more complex currents than considered here. For future work, we plan to use a more realistic mobility model to analyze the performance of DNR-Positioning.

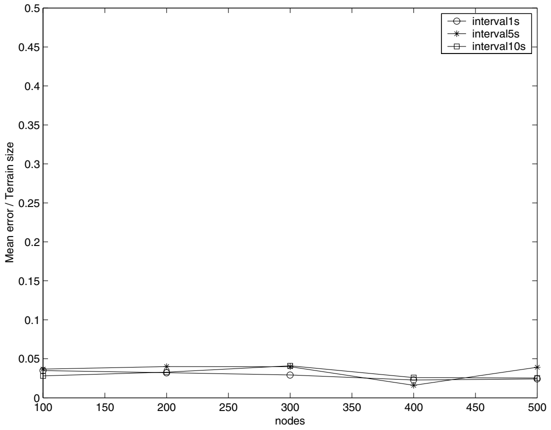

Figure 9: Ratio of error in mobile scenario with triangulation.

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