Spatial Dependencies Between Velocities of Underwater Drifting Nodes

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ABSTRACT

In this paper we investigate spatial dependencies of ocean currents, which can be used as a-priori information for localization and tracking algorithms in underwater acoustic networks. We utilize velocity estimation of a tracked node as a measure to show these spatial dependencies. Results from both simulation and sea trials show a good fit between estimated velocity and actual one, indicating strong spatial dependencies of the ocean current.

1. INTRODUCTION

Spatial dependencies of ocean current velocity fields might be useful to assist localization and tracking under water. To assess and illustrate these dependencies, we consider an underwater acoustic communication network consisting of $K$ anchor nodes and one tracked node, and utilize available information of velocity $v_k$ of anchor nodes $k = 1 \ldots K$ to estimate the velocity of a tracked node $v_{TR}$. Since acoustic ranging and position information of anchor nodes is required for underwater acoustic localization [5] anyhow, the velocity of anchor nodes can be extracted at the tracked node.

Spatial dependency has been assumed in [4] where an Acoustic Doppler Current Profiler is used to measure ocean currents at different depths in order to estimate velocity for dead reckoning (DR) navigation. Alternatively, in [2] a collaborative localization algorithm for fleets of vertically sinking drifters is presented.

In this paper, we consider ocean current-induced node motion, and assume a slowly changing current field. However, self-propelled motion is also allowed by adding the resulting propelled velocity to the estimated velocity $v_{TR}$.

2. METHOD

2.1 System Model

Our setup consists of $K$ anchor nodes with known location, which frequently share location information with a tracked node via acoustic communication, and thereby velocity. In addition, using acoustic ranging, the tracked node is assumed aware of approximate distance $d_k$ to each of the $K$ anchor nodes. In this paper, we limit our methods to two dimensions. However, extension is straightforward.

For $v_{TR}$ and $\hat{v}_{TR}$ being the true and estimated velocity of the tracked node, respectively, our objective is to minimize the relative velocity estimation error

$$e_v = \frac{\|v_{TR} - \hat{v}_{TR}\|}{\|v_{TR}\| + \|\hat{v}_{TR}\|},$$

which includes direction and velocity errors and is 1 if the vectors point in opposite directions and 0 if the vectors are the same. In the following, we present three algorithms for estimating $v_{TR}$.

2.2 Velocity Estimation

As mentioned before, we use ranging information to anchor nodes. A noisy version of this range is available to the tracked node as part of the localization. However, as the estimation error is expected to be much larger than ranging accuracy, the effect of noise on our approach is small.

2.2.1 Nearest Neighbor (NN)

The simplest method to estimate $\hat{v}_{TR}$ is by choosing

$$\hat{k} = \arg\min_{k=1 \ldots K} (d_k),$$

and setting

$$\hat{v}_{TR} = v_k.$$  \hspace{1cm} (3)

The major drawback of the NN method is that velocity information of anchor nodes, other than $\hat{k}$, is not used.

2.2.2 Weighted Superposition (WSP)

As first proposed by [3], in the WSP method velocities of anchor nodes are superimposed such that

$$\hat{v}_{TR} = \frac{\sum_{k=1}^{K} w(d_k) \cdot v_k}{\sum_{k=1}^{K} w(d_k)},$$  \hspace{1cm} (4)

where $w(d_k)$ is a weight function. We chose $w(d_k) = d_k^{-2}$ as a pragmatic choice in the absence of a statistical model for spatial dependencies.

2.2.3 Least Squares (LS)

Assuming that ocean currents change linearly over space, estimating $v_{TR}$ can also be interpreted as estimating two planes, one each for the $x$- and $y$-coordinate of the velocity. We formulate the problem as

$$\begin{pmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ \vdots & \vdots & \vdots \\ x_K & y_K & 1 \end{pmatrix} \begin{pmatrix} a_x \\ a_y \\ b_x \\ b_y \\ c_x \\ c_y \end{pmatrix} = \begin{pmatrix} v_{x,1} & v_{y,1} \\ v_{x,2} & v_{y,2} \\ \vdots & \vdots \\ v_{x,K} & v_{y,K} \end{pmatrix},$$ \hspace{1cm} (5)

where $\begin{pmatrix} x_1 & y_1 & 1 \\ \vdots & \vdots & \vdots \\ x_K & y_K & 1 \end{pmatrix}$ is the measurement matrix, $\begin{pmatrix} a_x \\ a_y \\ b_x \\ b_y \\ c_x \\ c_y \end{pmatrix}$ are the parameters to be estimated, and $\begin{pmatrix} v_{x,1} & v_{y,1} \\ v_{x,2} & v_{y,2} \\ \vdots & \vdots \\ v_{x,K} & v_{y,K} \end{pmatrix}$ are the true velocities of the tracked node.
with anchor position matrix $P$ (in Cartesian coordinates), anchor velocity matrix $V$, and plane coefficients in matrix $C$, wherein the coefficients $a(x,y)$, $b(x,y)$, and $c(x,y)$ describe the plane for the $x$- and $y$-coordinate of the velocity, respectively. Solving for $C$ yields

$$C = \left( P^T \cdot P \right)^{-1} \cdot \left( P^T \cdot V \right),$$

and

$$\hat{v}_x^T = \begin{pmatrix} x_{TR} \\ y_{TR} \end{pmatrix} \cdot C.$$  

Note that for the LS method at least three anchor nodes are required. Due to the matrix inversion in (6), the LS method is sensitive to short distances between anchor nodes and noisy velocity measurements $v_k$.

3. RESULTS

3.1 Model-based Results

In this section, we present model-based simulation results by using the Shallow Water Hydrodynamic Finite Element Model (SHYFEM) [6] to simulate time-varying current velocity fields. These are used to generate trajectories of anchor and tracked nodes, initially placed uniformly in an area of $2 \times 2$ km$^2$. Figure 1 shows the result of measure (1) for 1, 2, 4, and 6 anchor nodes with zero-mean Gaussian noise superimposed on the anchor velocity measurement. The average speed of tracked nodes is $E(\{v_{TR}\}) = 0.12$ m/s. We observe that error of velocity estimation increases with the variance of measurement noise, but decreases with the number of anchor nodes. For low measurement noise, $e_v$ is on average below 20%, which shows strong spatial dependencies between velocities of anchors and the tracked node.

3.2 Sea Trial

To validate our model-based results, we also use sea trial data, collected off the shores of Israel (see description in [1]). The trajectories of four drifting yachts have been measured using Global Positioning System (GPS) receivers. For the evaluation of our proposed methods, one of the yachts has been chosen as the tracked node, while the other three served as anchor nodes. Figure 2 shows the time-series of measured and estimated speed and direction using the three methods presented in Section 2.2. While the LS method seems best in most cases, the average results shown in Table 1 with magnitude $v$ and angle $\phi$ of $v$ in polar coordinates, imply that the WSP method outperforms both NN and LS methods. This is because the NN method does not use all the provided velocity information and the LS method is sensitive to scenarios with anchor nodes close to each other.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean absolute errors for sea trial data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(</td>
<td>v_{TR} - v_{TR}</td>
</tr>
<tr>
<td>0.114</td>
<td>0.113</td>
</tr>
<tr>
<td>$E(</td>
<td>\phi_{TR} - \phi_{TR}</td>
</tr>
<tr>
<td>0.371</td>
<td>0.255</td>
</tr>
</tbody>
</table>

4. CONCLUSION

In this paper we suggested three approaches for velocity estimation of tracked underwater drifting nodes to show spatial dependencies of the current velocity field. Results suggest strong spatial dependencies, that could be used to assist localization and tracking systems. In future work, we plan to develop a self-obtained measure to detect unreliable velocity estimates in order to reject inaccurate estimates. Then, a tracking algorithm, taking into consideration velocity estimation, would be developed.

5. REFERENCES


Figure 1: Average velocity estimation error $e_v$ from (1) for the WSP method as function of the variance of velocity measurement noise.

Figure 2: Estimates for speed (a) and direction (b) for the three methods compared to actual values for sea trial data.