Localization of Mobile Nodes in an Underwater Distributed Antenna System

Patrick Carroll, Katherine Domrese, Hao Zhou, Shengli Zhou, and Peter Willett
Presented By: Zheng Peng

Dept. of Electrical and Computer Engineering
University of Connecticut

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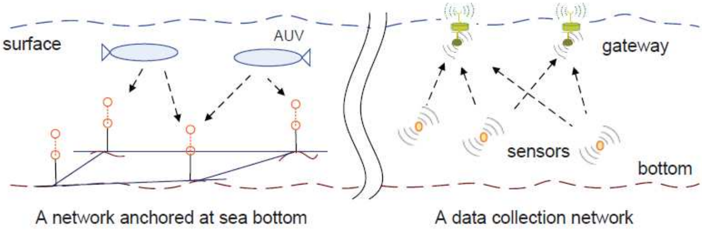


- Distributed Antenna System (DAS) networks are a common feature in current underwater networks
- Key features:
  - Secondary communication link.
  - Multiple acoustic nodes at different locations.
  - Centralized Processing

Modem Advancements

Current acoustic OFDM modem technology has advanced beyond what initially was available for localization.

- Any message sent, regardless of content, can accurately estimate the relative Doppler speed of the transmitter and receiver
- With stationary receivers, such as DAS network antennas, the Doppler speed of any mobile node can be accurately estimated.

With the additional Doppler information, position and instantaneous velocity can both be estimated. With one message from N antennas, we obtain:

- N time-of arrivals
- N Doppler speed estimates.

Localization Algorithm Derivation

First, we form the time-difference of arrival (TDOA) estimate:

$$\Delta t_{n,1}(k) = \hat{t}_{\mathrm{s}n}(k) - \hat{t}_{\mathrm{s}1}(k) \tag{1}$$

which is equivalently:

$$\Delta t_{n,1}(k) = \frac{1}{c} d_{\mathrm{s}n}(k) + O_s(k) + w_{rn}(k) - \frac{1}{c} d_{\mathrm{s}1}(k) + O_s(k) + w_{r1}(k) \tag{2}$$

$$= \frac{1}{c}[d_{\mathrm{s}n}(k) - d_{\mathrm{s}1}(k)] + w_{rn}(k) - w_{r1}(k) \tag{3}$$

With the timing offset eliminated, and assuming that our noises are zero-mean additive Gaussian, the ML estimator for the position would be:

$$[\hat{x}(k), \hat{y}(k), \hat{z}(k)] = \underset{(x(k),y(k),z(k))}{\arg\min} \sum_{n=2}^{N} [(c\Delta t_{n,1}(k) - d_{\mathrm{s}n}(k) - d_{\mathrm{s}1}(k)]^2 \tag{4}$$

Doppler Information

The Doppler shift measured at each node can be represented as:

$$v_n(k) = |v_n(k)|(\cos(\alpha(k)) + \tan(\gamma(k))) \tag{5}$$

where

$$|v_n(k)| = \sqrt{\dot{x}_{\mathrm{s}}(k)^2 + \dot{y}_{\mathrm{s}}(k)^2 + \dot{z}_{\mathrm{s}}(k)^2} \tag{6}$$

- The total angle between an antenna and the active node is denoted as:

$$\cos(\alpha(k)) = \frac{x_{\mathrm{s}}(k) - x_n}{r_n(k)} + \frac{y_{\mathrm{s}}(k) - y_n}{r_n(k)} \tag{7}$$

$$\tan(\gamma(k)) = \frac{z_{\mathrm{s}}(k) - z_n}{r_n(k)} \tag{8}$$

where

$$r_n(k) = \sqrt{(x_{\mathrm{s}}(k) - x_n)^2 + (y_{\mathrm{s}}(k) - y_n)^2 + (z_{\mathrm{s}}(k) - z_n)^2} \tag{9}$$

Localization Algorithm Derivation

We define the complete state vector:

$$\Theta(k) = [x(k), y(k), z(k), \dot{x}(k), \dot{y}(k), \dot{z}(k)] \tag{10}$$

Again assuming zero-mean additive Gaussian noise the joint likelihood for the active node s is:

$$\hat{\Theta}(k) = \arg\min_{\Theta(k)} \frac{1}{2(c\sigma_t)^2} \sum_{n=2}^{N} [(c\Delta t_{n,1}(k) - (d_{\mathrm{s}n}(k) - d_{\mathrm{s}1}(k))]^2 + \frac{1}{\sigma_v^2} \sum_{n=1}^{N} (\hat{v}_n(k) - v_n(k))^2 \tag{11}$$

where σ_v is the Doppler speed measurement noise standard deviation in m/s.

- Solved by first using a coarse search grid for initial point, then gradient-descent search to for solution.

Tracking

Tracking filters in this scenario serves two purposes:

- TDOA only measurements can only estimate velocity with filtering; this acts as a baseline for comparison
- Most mobile elements will employ basic filtering; examine if Doppler information can improve tracking.

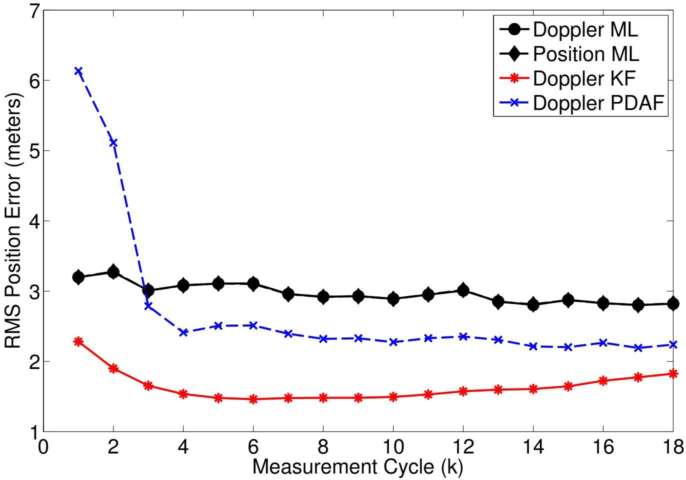
We use a Kalman Filter (KF) and Probabilistic Data Association Filter (PDAF) for approximate straight-line motion.

- The state for the Doppler-aided KF and PDAF are provided a 6-state measurement and track 9 states (3D position, velocity and acceleration).
- We present only the KF results here and in the short paper. Full paper will have both.

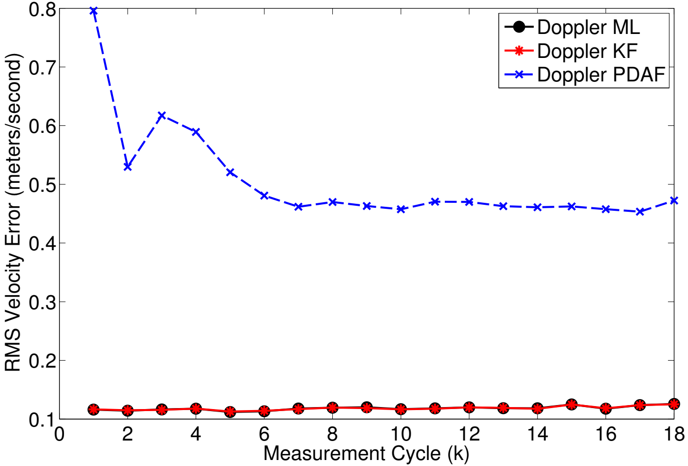
Simulations

- Four antenna nodes located on the same z-plane defined as $z = 0$ arranged in a square separated by 300 m.
- Active node begins positioned in this grid at $(x, y, z) = (75, 25, 10)$ in meters
- Node has constant velocity defined as $(\dot{x}, \dot{y}, \dot{z}) = (-.5, .7, .4)$ in meters/second.
- There are 20 total measurements during the scenario.
- 1000 Monte-Carlo runs.
- The simulated noise level is $\sigma_r = 0.825$ m and $\sigma_v = .07$ m/s.
- Messaging intervals of 5 s.

Simulated Position Error for Mobile Node



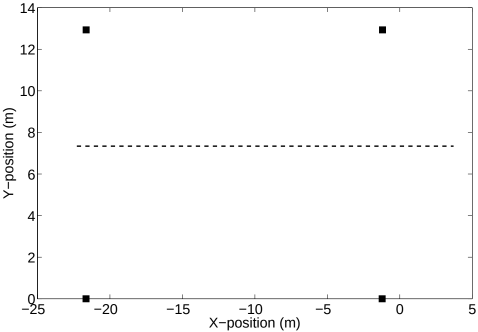
Simulated Velocity Error for Mobile Node



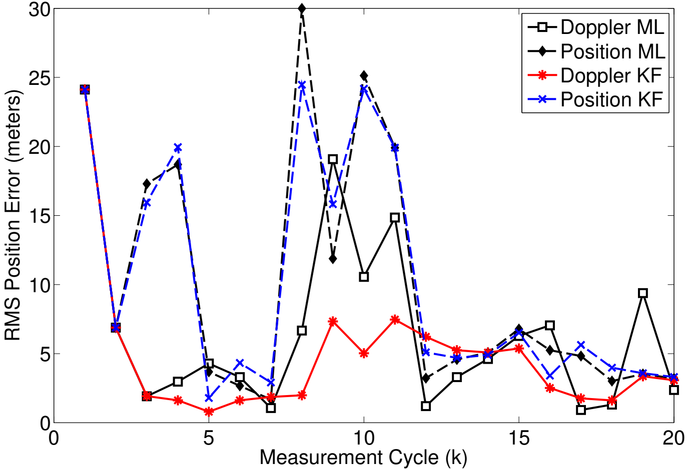
Pool Testing

- Pool testing was performed at the UCONN Brundage Pool on June 24th, 2014.
- The pool is approximate 24 meters by 13 meters, and the four antenna nodes were deployed at the corner edges.
- The active node was moved along the entire length of the pool at a constant velocity, 7.5 m away from the side.
- Active node transmits a message every 4 seconds, approximately 20 times total.

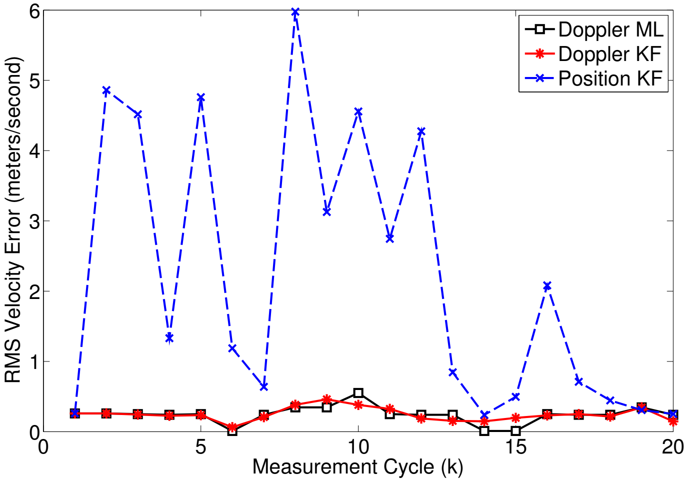
Node Layout During Pool Test



Position Error for Mobile Node During Pool Test



Velocity Error for Mobile Node During Pool Test



Summary

- Derived a mobility oriented localization algorithm that exploits advances and trends in underwater acoustic networking.
- Presented algorithms and simulations of the solution.
- Tested the algorithm in a controlled environment and performed analysis of the sources of error present in results.
- Future work includes examining additional tracking algorithms and investigating possible larger scale testing.