Cooperative positioning using range-only measurements between two AUVs

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***Abstract*—This paper presents a cooperative positioning system between two autonomous underwater vehicles (AUVs). Each AUV is equipped with some navigational sensors. However, AUVs with different tasks have different navigational capabilities. By introducing acoustic communication between AUVs, information from multiple AUVs can be fused to give a more accurate position estimates to AUVs with poorer navigational capabilities. We present results from a field trial where a lawnmower mission is executed by a survey AUV with poor navigational sensors while another AUV with higher positioning accuracy plays the role of a beacon AUV. The beacon AUV's task is to help improve the survey AUV's position accuracy by providing it regular range updates from various locations. An Extended Kalman Filter (EKF) was implemented to fuse the range information updates with the navigational sensor data on the survey AUV. We were able to avoid unbounded error growth in the position estimate of the survey AUV in our experiments through cooperative positioning between two AUVs using range-only measurements.**

I. Introduction

The past decade has seen a significant increase in interest in the use of autonomous underwater vehicles (AUVs) for maritime operations. Many research and commercial AUVs have been developed and tested [1], [2], [3]. One of the challenges that all AUVs have to face is that of underwater navigation, especially since GPS signals cannot be received underwater. Although Inertial Navigation Systems (INS) and Doppler Velocity Logs (DVL) can help AUVs track their position underwater, these systems tend to be very expensive and the position estimates from the systems suffer from an unbounded increase in error over time while the AUVs remain submerged. To solve this problem, some AUVs opt to surface often and use a GPS to correct the position estimate. Other AUVs employ fixed beacons in the form of Long Baseline (LBL) or Ultra Short Baseline (USBL) acoustic systems to estimate their positions underwater [4] at the cost of substantial support infrastructure cost and deployment effort.

The idea of cooperative navigation between multiple AUVs or AUVs and surface vessels has been explored by some researchers [5], [6], [7]. Cooperative navigation between AUVs can allow a team of AUVs to operate although only a limited number of AUVs in the team may have the sensors required for accurate position estimation. A team of small low-cost AUVs known as STARFISH (Small Team of Autonomous Robotic "Fish") has been developed at the ARL (National University of Singapore) [8]. These AUVs can be configured to have different payloads and capabilities, and are ideal candidates for benefiting from cooperative navigation. Some AUVs in the team can be configured with DVL payloads for accurate navigation, while others may carry sensor payloads such as sidescan sonars required for surveying. All STARFISH AUVs are equipped with acoustic modems that can be used for range estimation. Information fusion of position and range estimates from several AUVs can help reduce noise in the final position estimates used for navigation.

In this paper, we consider a cooperative survey mission with two AUVs. One of the AUV is configured with sensors required for the survey, but has poor positioning accuracy due to lack of DVL. The other AUV is configured with a DVL and therefore has good positioning accuracy, but lacks the sensors needed for the survey mission. Together, they are tasked to conduct a survey where the AUV with the sensor executes a lawnmower path over the survey area. We shall call this AUV the *survey AUV*. The AUV with DVL helps the survey AUV improve its position estimate by transmitting its own position and measuring the range to the survey AUV periodically. We call this AUV the *beacon AUV*. The position and range information is combined by the survey AUV with its own dead reckoning position estimate using an Extended Kalman Filter (EKF).

Position estimation using range-only measurements has been studied by many researchers [9], [10], [11], [12]. In many cases, the problem has only been considered in the context of fixed beacons, while in other cases (see [12]) the beacon is assumed to some arbitrary zig-zag pattern. In our work, we allow the beacon AUV to plan its path based on the knowledge of the survey path and an objective to minimize the error of the survey AUV [13]. We present results from a preliminary experiment using STARFISH AUVs (see Fig. 1) to determine the resulting positioning accuracy of the survey AUV.

II. Position Estimation

A. Navigational sensors

The advanced navigation payload of the STARFISH beacon AUV houses a DVL that yields an accurate velocity estimate

Fig. 1. The 2 AUVs for cooperative positioning

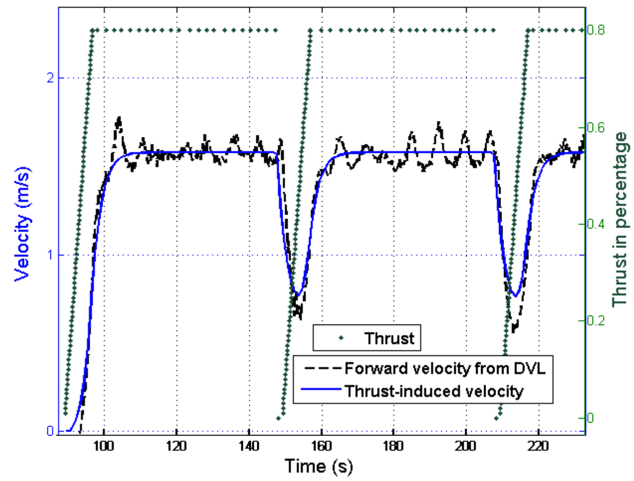

Fig. 2. Thruster model estimating forward velocity of AUV compared with the velocity measurement from DVL. The dotted line shows the thruster control signal.

with respect to the seabed. Alternatively, we also estimate the body-frame velocity from the force produced by the thruster in tail section [14]. If we know the force T produced by the thruster, the thruster-induced forward velocity u_t can be estimated from:

$$m\dot{u}_t = gT - \frac{1}{2}C_d \rho A u_t^2 \tag{1}$$

where g is the gravitational acceleration, A is the AUV cross-section area, m is the mass of the AUV, ρ is the density of water and C_d is the drag coefficient. Hence the body-frame velocity vector $\mathbf{v}$ containing the velocities alonge the AUV's body-frame coordinates can be written as:

$$\mathbf{v} = \begin{bmatrix} v_x & v_y & v_z \end{bmatrix}^T \tag{2}$$

$$= \begin{bmatrix} u_t & 0 & 0 \end{bmatrix}^T \tag{3}$$

Fig. 2 shows a comparison between the thrust-induced velocity estimate and the DVL velocity measurement in forward direction during a lake trial. Although there are some small differences between the measured velocity of the AUV and the thrust-induced velocity estimate, our model can be used to obtain a good estimate of the velocity of the AUV in the absence of a velocity measurement sensor. However, since the model can only estimate the velocity with respect to water, we expect the estimate to be a poor estimate of the velocity with respect to the seabed in presence of strong ocean currents.

An AUV equipped with DVL can use the measured velocity and estimated thruster-induced velocity to estimate the motion of the AUV due to ocean currents. This estimate of ocean current can be used by the command and control system in path planning and vehicle control. If the DVL loses a bottom lock, the ocean current estimate may also be used along with the thruster-induced velocity estimate to estimate the velocity with respect to the seabed. The ocean current estimate may also be transmitted to other AUVs in the same operational area (and therefore assumed to be experiencing similar ocean currents), so that they may use it in their velocity estimation and command and control.

B. Acoustic ranging

The survey and the beacon AUV are equipped with underwater modems to communicate with each other, as shown in Fig. 3. By measuring the propagation delay between the AUVs, the modems can estimate the range between the AUVs. If timing synchronization is available, a 1-way propagation delay can be measured and used to compute the range between the AUVs. In the absence of time synchronization, a 2-way propagation delay has to be used to compute the range. In either case, the position of the beacon AUV and the estimated range between the AUVs has to be communicated to the survey AUV periodically.

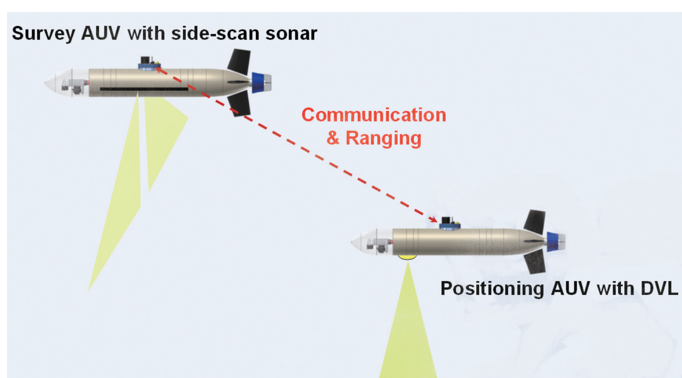

Fig. 3. The 2 AUVs for cooperative positioning

C. Path-planning for cooperative positioning

The path to be followed by the survey AUV is pre-planned. The beacon AUV's path is planned through a series

$$
\begin{aligned}
\mathbf{R}_k &= \mathbf{R}(\beta)\mathbf{R}(\theta)\mathbf{R}(\psi) \\
&= \begin{bmatrix} \cos\beta\cos\theta & \cos\beta\sin\theta\sin\psi+\sin\beta\cos\psi & -\cos\beta\sin\theta\cos\psi+\sin\beta\sin\psi \\ -\sin\beta\cos\theta & -\sin\beta\sin\theta\sin\psi+\cos\beta\cos\psi & \sin\beta\sin\theta\cos\psi+\cos\beta\sin\psi \\ \sin\theta & -\cos\theta\sin\psi & \cos\theta\cos\psi \end{bmatrix}
\end{aligned} \tag{5}
$$

of sequential decisions made by the onboard command and control system during the mission, using information about the survey AUV's desired path. The decisions are made with an optimization criteria that minimizes the error of the survey AUV's position, avoids collision between the AUVs, enforces geofencing constraints and attempts to keep the AUVs with communication range.

Fig. 4 shows that the error estimate of survey AUV position is reduced in the radial direction of the ranging circle centered at beacon AUV, each time a range estimate becomes available. However, the error in the tangential direction remains unchanged. The cooperative positioning algorithm for the beacon AUV uses the estimated error ellipse of the survey AUV's position to plan its own movement. If the beacon AUV can move such that the next range measurement occurs along the direction of the major axis of the error ellipse, the position error of the survey AUV can be minimized. This is the key idea underlying the path planning for the beacon AUV. The position estimation algorithm presented in this paper is not critically dependent on the exact details of the beacon AUV's path planning algorithm. Hence, we do not present that algorithm in detail in this paper, but instead refer the interested reader to [13]. In this paper, we focus on the algorithm to use the range information between the two AUVs to improve the estimate of the position of the survey AUV.

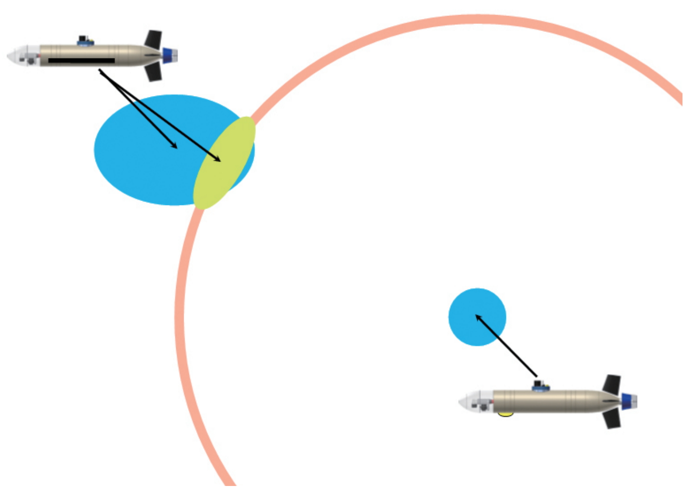

Fig. 4. Illustration of error estimates by range measurements

D. Position estimation using range information

The position estimation utilizes Kalman filtering [15] and is divided into two steps as described below.

1) Dynamic system model: The state $\mathbf{x}_{k+1}$ is the 3-dimensional position vector at time step $k+1$ containing the east, north and depth in navigation frame. It is evolved from its previous state at time step k according to:

$$\mathbf{x}_{k+1|k} = \mathbf{x}_k + \mathbf{R}_k\mathbf{v}_k\tau + \mathbf{w}_k \tag{4}$$

where the 3×3 rotation matrix $\mathbf{R}_k$ transforms body-frame velocities $\mathbf{v}_k$ in (2) into the navigation frame, τ is the elapsed time from time k to $k+1$ and the process noise $\mathbf{w}_k$ is assumed zero mean multivariate Gaussian noise with covariance $\mathbf{Q}_k$. $\mathbf{R}_k$ is formulated from the 3-axis orientation measured by the digital compass and tilt sensors.

We denote $\hat{\mathbf{x}}_k$ as the position estimate at time step k. We estimate the position at time step $k+1$ via the prediction model in (4) to give us $\hat{\mathbf{x}}_{k+1|k}$. When the range or GPS measurement at time step $k+1$ becomes available, we combine the measurement with the estimate $\hat{\mathbf{x}}_{k+1|k}$ to give us $\hat{\mathbf{x}}_{k+1}$.

With the 3 degree of freedom rotation angles - yaw β, pitch θ and roll ψ, the transformation matrix $\mathbf{R}_k$ can be written as the multiplication of a series of basic rotations in (5). The rotation angles are derived from onboard compass measurement - bearing b, pitch p and roll r at time k as $\sin\psi = -\frac{\sin r_k}{\cos p_k}$, $\beta = -b_k$ and $\theta = p_k$. The system belief is updated with noise covariance Q_k according to the performance of the navigation sensor used. The survey AUV has larger error covariance since its body-frame velocity $\mathbf{v}_k$ is only calculated from the thrust-induced velocity estimate. In this dynamic model, the estimated error covariance matrix $\hat{\mathbf{P}}$ is predicted as:

$$\hat{\mathbf{P}}_{k+1|k} = \hat{\mathbf{P}}_k + \mathbf{Q}_k \tag{6}$$

2) Measurement Model: The observation comes from either GPS or range measurement. While GPS provides a linear update of the position vector $\mathbf{x}$, range measured between the two AUVs corrects accumulated position error of survey AUV deadreckoning through linearization [16]. Firstly the range measurement is modeled as:

$$z_{k+1} = h(\mathbf{x}_{k+1}) = \|\mathbf{x}_{k+1} - \mathbf{x}^B_{k+1}\| + \sigma_{k+1} \tag{7}$$

where $\|\mathbf{x}_{k+1} - \mathbf{x}^B_{k+1}\|$ is the Euclidean distance between position of survey AUV $\mathbf{x}_{k+1}$ and beacon AUV $\mathbf{x}^B_{k+1}$. The observed range measurement has a zero mean Gaussian noise σ_{k+1} with covariance $\mathbf{R}_{k+1}$. The estimated position error of beacon AUV $\hat{\mathbf{x}}^B_{k+1}$ is relatively low and incorporated into σ_{k+1}. The observation matrix is the Jacobian defined below:

$$
\begin{aligned}
\mathbf{H}_{k+1} &= \frac{\partial h}{\partial \mathbf{x}}|\hat{\mathbf{x}}_{k+1|k} \\
&= \frac{(\hat{\mathbf{x}}_{k+1|k} - \hat{\mathbf{x}}^B_{k+1})^T}{\|\hat{\mathbf{x}}_{k+1|k} - \hat{\mathbf{x}}^B_{k+1}\|}
\end{aligned} \tag{8}
$$

The position state vector of survey AUV is updated as:

$$\hat{\mathbf{x}}_{k+1} = \hat{\mathbf{x}}_{k+1|k} + \mathbf{K}_{k+1}\tilde{y}_{k+1} \tag{9}$$

where $\mathbf{K}_{k+1}$ is the optimal Kalman gain and $\tilde{y}_{k+1}$ is the measurement residual between the measured and predicted ranges between the two AUVs.

$$\tilde{y}_{k+1} = z_{k+1} - \|\hat{\mathbf{x}}_{k+1|k} - \hat{\mathbf{x}}^B_{k+1}\| \tag{10}$$

$$\mathbf{S}_{k+1} = \mathbf{H}_{k+1}\hat{\mathbf{P}}_{k+1|k}\mathbf{H}^T_{k+1} + \mathbf{R}_{k+1} \tag{11}$$

$$\mathbf{K}_{k+1} = \hat{\mathbf{P}}_{k+1|k}\mathbf{H}^T_{k+1}\mathbf{S}^{-1}_{k+1} \tag{12}$$

The error estimate at time $k+1$ is updated as:

$$\hat{\mathbf{P}}_{k+1} = (I - \mathbf{K}_{k+1}\mathbf{H}_{k+1})\hat{\mathbf{P}}_{k+1|k} \tag{13}$$

Typically the depth of AUV is specified in a mission and not altered by the path planning algorithm. The depth sensor and altimeter are used to measure the vehicle depth. Therefore in this paper we only display the 2-dimensional positioning.

III. Experimental Setup and Results

We explored the effectiveness of the cooperative positioning initially through simulation and then via several field experiments.

A. Lake trial

During the field trial in a lake, the survey AUV was designated to perform a survey mission of a 130×100 m area, while the beacon AUV chose a path shown in Fig. 5. The solid line is the planned path for survey AUV and the dashed line is the path computed by beacon AUV to assist positioning of the survey AUV. Fig. 6 shows the position estimates of survey AUV from the EKF with range-only measurements as well as the actual position measured via GPS. In this experiment, the AUVs were at the surface so that a GPS fix was available as ground truth. Both AUVs were set to 60% thrust. Simulated range measurements (using the known GPS positions rather than acoustics) were made every 20 seconds and fed into the EKF. The position updates can clearly be seen as discontinuities in position estimates when the EKF changes its belief substantially as a result of range information becoming available. In order to compare the positioning accuracy with and without cooperative positioning, we also tracked the position estimate of the survey AUV purely by dead reckoning. The error plots in Fig. 7 demonstrate that range updates fused by EKF indeed improved the position accuracy of the survey AUV, and ensured that the position error did not grow without bound.

B. Sea trial

We carried out a number of tests at Selat Pauh, an anchorage area south of Singapore in January 2010. We present results from a mission that surveyed a 150×200 m area in Figs. 8–11. A survey AUV mission without range updates (only dead reckoning) is shown in Fig. 8. Since the survey AUV has no sensor to sense motion over the seabed, it was unable to account for ocean currents during this mission. The position

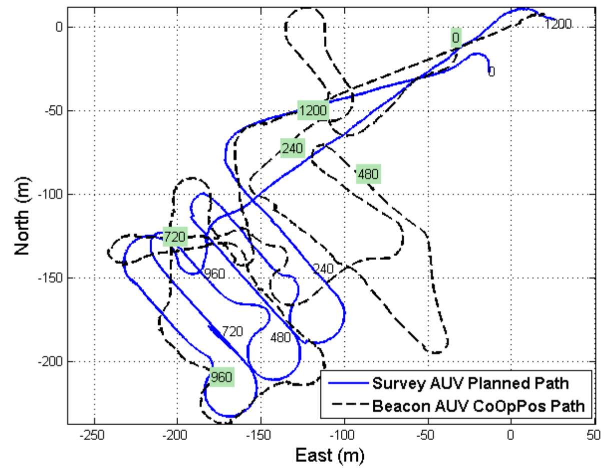

Fig. 5. AUV paths for lawnmower mission survey during lake trial

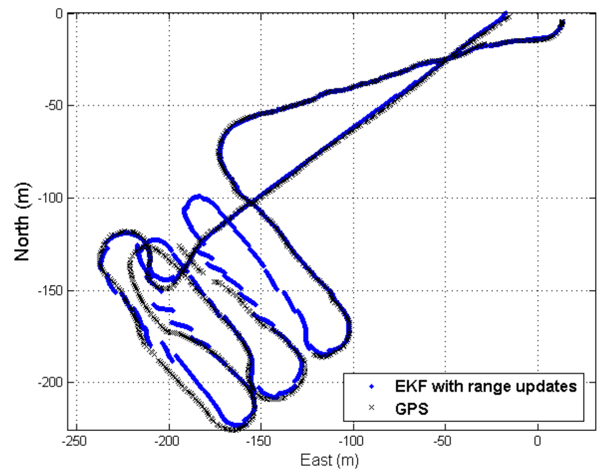

Fig. 6. Survey AUV: EKF with range updates (cooperative positioning) compared with GPS data during lake trials

estimate used by the command and control system was based on thrust-induced velocity only. Although the AUV attempted to follow the survey path, the actual path (from GPS) has a significant eastward drift due to ocean currents. Fig. 9 shows the beacon AUVs chosen path to aid the survey AUV in this mission. In this experiment, the survey AUV was set to use 70% thrust, while the beacon AUV was set to use 80% thrust. With range updates from the beacon AUV, the EKF in the survey AUV was able to track the position of the survey AUV with increased accuracy. The control and command system was able to use this information to better direct the survey AUV to the designated survey path as seen in Fig. 10. Again we can clearly see the discontinuities in position estimates when the EKF updates the estimate based on range information. As seen in Fig. 11, the position error of survey AUV using range measurements was significant lesser

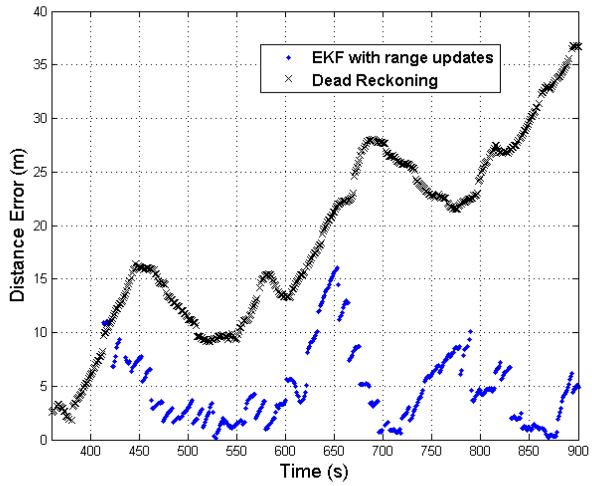

Fig. 7. Position error of EKF with range updates (cooperative positioning) as compared with dead reckoning (single AUV positioning) during lake trials

(and bounded) as compared to the single AUV surveying.

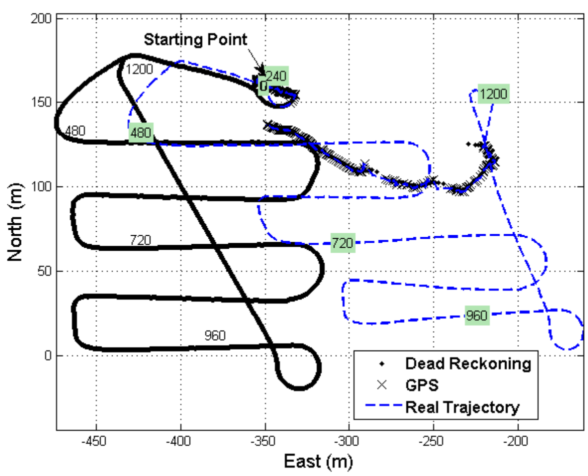

Fig. 8. Survey AUV: drift due to ocean currents during sea trials (single AUV positioning)

IV. Conclusion

In this paper, we presented results from lake and sea experiments with cooperative positioning using range-only measurements from two AUVs engaging in a survey mission. An Extended Kalman filter (EKF) was implemented to estimate and survey AUV position by fusing the range information available. The position error of the survey AUV grows rapidly without aid from the beacon AUV, but can be kept small when a beacon AUV with good positioning sensors is available to support the survey mission.

With growing number of AUVs in the STARFISH team, systems that can localize and navigate a team of AUVs with heterogenous capabilities can be realized. We are exploring

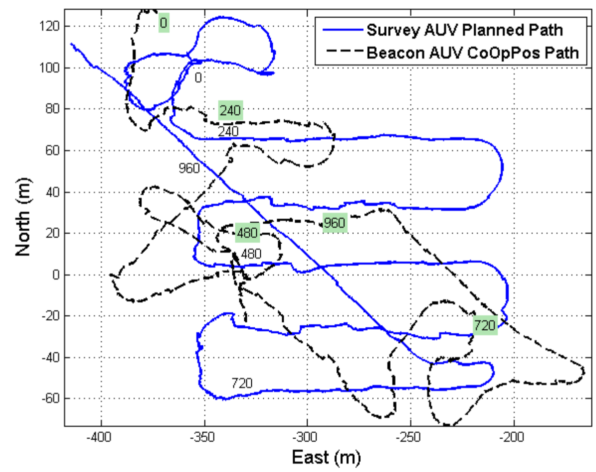

Fig. 9. AUV paths for lawnmower mission survey during sea trials

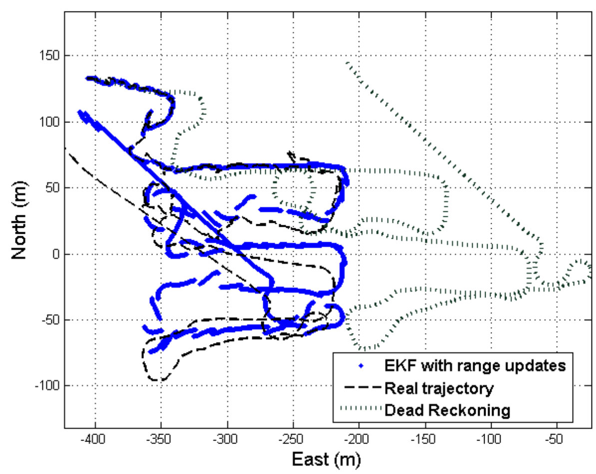

Fig. 10. Comparison EKF with ranging (cooperative positioning) and dead-reckoning (single AUV positioning) during sea trials

effective sensor fusion techniques that will utilize available information from various sensors available across the team of heterogenous AUVs.

Acknowledgment

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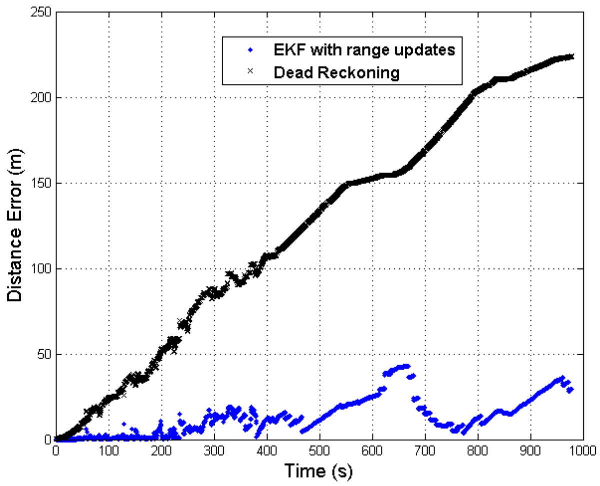

Fig. 11. Position error of EKF with range updates (cooperative positioning) as compared with dead reckoning (single AUV positioning) during sea trials

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