AUV State Estimation and Navigation to Compensate for Ocean Currents

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***Abstract*—This paper presents a novel approach to water-current compensation for autonomous underwater vehicle (AUV) state estimation and navigation. The approach is twofold: first, an extended Kalman filter estimates both the AUV state and water-currents in the north and east directions; second, these water-current estimates are used in a modified heading controller to calculate a current-compensated desired heading for the AUV to follow. Both the extended Kalman filter and modified heading controller are presented and simulated using historical experimental data for noise estimation. The presented results are a promising first step towards further testing and real-time implementation on the AUVs for localization and navigation in ocean environments.**

Keywords— AUV, EKF, LBL, Localization, Navigation, Ocean Current Compensation

I. Introduction

The ability to make scientific measurements in ocean environments is of particular interest to the US Navy. One approach the Office of Naval Research is exploring is equipping autonomous underwater vehicles with a variety of sensors in order to conduct oceanographic survey measurements. In response to this need, the University of Idaho (UI) has created a fleet of autonomous underwater vehicles (AUVs) with the goal of performing such measurements.

Oceanic survey measurements require both accurate sensing technology and localization. That is, a measurement only has value if its time, location, and orientation are accurately known. When using AUVs to conduct such measurements this requires accurate knowledge of position and orientation to be temporally synced with each acquired measurement. Presently each UI AUV uses an extended Kalman filter (EKF) to estimate its own position (north and east), speed, and heading as it navigates. This EKF utilizes range measurements from a long-baseline (LBL) array of transponders at known locations as well as heading and propeller speed measurements from onboard sensors. This approach has performed well when water currents were negligible. In the most recent field testing, however, the magnitude of ocean currents presented a more significant challenge for state estimation and navigation.

A notable challenge with AUV state estimation is the lack of ground truth for speed measurement. A Doppler velocity log (DVL) may be used to acquire high-accuracy absolute-velocity measurements [1], but their large physical size and high cost make them unsuitable for the AUVs being developed at UI. Presently, speed measurement for an UI AUV is determined from a correlation to propeller speed (RPM). Unlike the DVL, this is a relative-speed measurement, referred to herein as speed through water (STW). STW is a good estimate of speed over ground (SOG) when water currents are negligible, but this is not the case in most ocean environments.

One possible solution to the navigational challenge of ocean currents is to estimate a speed and heading bias in the EKF. While navigating in a single direction, this adaptation allows the AUV to better determine its SOG. However, a large change to the desired navigational direction (such as a 90 or 180 degree turn) also causes a large change to the local frame of the AUV. And because water currents exist in the global frame, the SOG estimate is no longer valid, and the onboard EKF will have to relearn the speed and heading biases.

This paper presents a novel approach for estimation and navigation in the presence of ocean currents. This approach uses an EKF to estimate water currents in both north and east directions, which are combined with the STW estimate to give a better estimate of SOG. This information is then used for navigation and control; this approach also includes a modification to the MOOS (Mission Oriented Operating Suite) heading controller [2] that offsets future ghost waypoints to account for the estimated currents.

Previous approaches to navigation in ocean currents includes control based methods such as Lyapunov based adaptive control [3] and multivariable sliding mode control [4]. Another common approach, typically for ocean gliders, focuses on path planning [5, 6]. In [7] water current disturbances are estimated from the AUVs perturbed position. For the present application, state estimation is paramount, and thus we are developing an approach that first directly estimates water current as states in an EKF, similar to [8, 9]. Next, the water-current estimates are used separately for navigation and control.

II. Methods

A. AUV State and Ocean Current Estimation EKF

The proposed EKF has $n = 6$ states: east (E) and north (N) positions, STW (s), AUV heading (ψ), and east (C_E) and north (C_N) currents. Combining the STW and AUV heading estimates gives a velocity through water (VTW)

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estimate. Adding the east and north current to this VTW estimate gives a velocity over ground (VOG) estimate (see Fig. 1). This VOG estimate is used in the kinematic model of the EKF to propagate estimates of the east and north positions, is given in (1) below following the notation from [10]:

$$x_{k+1} = f(x_k, u_k, w_k) = \begin{bmatrix} E + s\sin(\psi)\Delta t + c_E\Delta t + w_E \\ N + s\cos(\psi)\Delta t + c_N\Delta t + w_N \\ s + w_s \\ \psi + \dot{\psi}\Delta t + w_\psi \\ c_E + w_{c_E} \\ c_N + w_{c_N} \end{bmatrix}_k ; \tag{1}$$

$$x = \begin{bmatrix} E & N & s & \psi & c_E & c_N \end{bmatrix}^T;$$
$$u = \dot{\psi};$$
$$w = \begin{bmatrix} w_E & w_N & w_s & w_\psi & w_{c_E} & w_{c_N} \end{bmatrix}^T,$$

where $\dot{\psi}$ is heading rate mapped from the onboard 3-axis gyroscope data, Δt the discrete time step, and w contains the process noise associated with each state in the model.

The measurement model for the EKF includes four range measurements ($r_A - r_D$) from acoustic transponders ($A - D$) at known locations, a propeller-speed-correlated STW measurement (s_m), and an AUV heading measurement (ψ_m) from a magnetic compass. These $m = 6$ measurements are related back to the states through a measurement model, given as:

$$y_k = h(x_k, i_k, v_k)$$
$$= \begin{bmatrix} \sqrt{(E-A_E)^2 + (N-A_N)^2 + (Z-A_Z)^2} + v_A \\ \sqrt{(E-B_E)^2 + (N-B_N)^2 + (Z-B_Z)^2} + v_B \\ \sqrt{(E-C_E)^2 + (N-C_N)^2 + (Z-C_Z)^2} + v_C \\ \sqrt{(E-D_E)^2 + (N-D_N)^2 + (Z-D_Z)^2} + v_D \\ s + v_s \\ \psi + v_\psi \end{bmatrix}_k ; \tag{2}$$

$$y = \begin{bmatrix} r_A & r_B & r_C & r_D & s_m & \psi_m \end{bmatrix}^T;$$
$$v = \begin{bmatrix} v_A & v_B & v_C & v_D & v_s & v_\psi \end{bmatrix}^T,$$

where Z is the AUV depth from an onboard highly-accurate pressure-based sensor, and v contains the noise associated with each measurement. Subscripts E, N, and Z on acoustic transponder locations $A - D$ indicate a specific coordinate (e.g. A_E is the east location of acoustic transponder A). These measurements, combined with the propagation model from (1), create an observable system.

B. EKF Covariance Matrices

The EKF uses three covariance matrices: the process noise covariance $Q_{n\times n}$, the measurement noise covariance $R_{m\times m}$, and the state covariance $P_{n\times n}$. These square matrices are typically diagonal (P only initially) with values corresponding to the square of the standard deviation of the corresponding process, measurement, or state, as the case may be. In each case, experimentally acquired data has been used as the basis for specifying these covariance values.

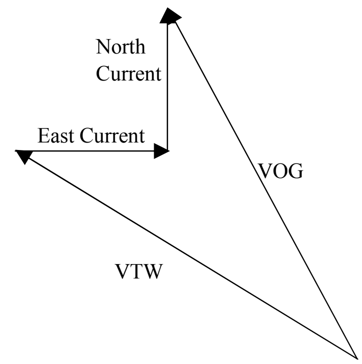

Fig. 1. Vector addition of VTW and ocean currents to calculate VOG.

The process noise covariance matrix includes any uncertainty associated with the estimations used to simplify the propagation model as well as any modeling errors. These estimations include discrete time step approximation, numerical integration order, etc. The covariance values were estimated based on typical error bounds associated with these approximations. Of particular interest are the covariance values for the currents; the small values ($1e-6\,\mathrm{m}^2/\mathrm{s}^2$) indicate that the currents are expected to be slow changing. This assumption creates a low-pass response to changes in ocean currents. The process noise covariance matrix is given as:

$$Q = \mathrm{diag}(0.01\mathrm{m}^2, 0.01\mathrm{m}^2, 1e-4\,\mathrm{m}^2/\mathrm{s}^2, \ldots$$
$$0.0076\mathrm{rad}^2, 1e-6\,\mathrm{m}^2/\mathrm{s}^2, 1e-6\,\mathrm{m}^2/\mathrm{s}^2). \tag{3}$$

The measurement noise covariance matrix includes 3 distinct values; one each for speed and heading and a common value for all range measurements. This common value for range measurement covariance was estimated by comparing each acquired acoustical range to an optimized, post-processed AUV position. Speed and heading covariance were estimated from statistical analysis of data collected during semi-steady-state operation of the AUVs. These values are combined in the measurement noise covariance matrix as:

$$R = \mathrm{diag}(10.9\mathrm{m}^2, 10.9\mathrm{m}^2, 10.9\mathrm{m}^2, 10.9\mathrm{m}^2, \ldots$$
$$0.0255\,\mathrm{m}^2/\mathrm{s}^2, 0.0102\mathrm{rad}^2). \tag{4}$$

The state covariance matrix is an estimate of the error associated with the current estimate of each state. This covariance matrix is initialized based on the variance of the measurements used to initialize the EKF. As speed and heading are affected significantly by the AUVs dive sequence, their covariance values are initialized above what is typically observed during steady-state. Additionally, as no real-time information is available to the UI AUVs about the ocean current, the covariance on the initial state estimation for both east and north currents are set high relative to the magnitude of currents that would be expected. The state covariance matrix is given as:

$$P = \text{diag}(25\text{m}^2, 25\text{m}^2, 2.25\,\text{m}^2/\text{s}^2, \ldots \\ 0.1218\text{rad}^2, 1\,\text{m}^2/\text{s}^2, 1\,\text{m}^2/\text{s}^2). \quad (5)$$

C. *Modified MOOS heading controller*

The UI AUVs navigate using preprogrammed waypoints and utilizing path following behavior based on the "track-line mode" of the MOOS-IvP Autonomy Project (www.moos-ivp.org). In previous research at UI this has performed well both in simulation and field testing when the VTW was comparable to the VOG [11, 12]. As these velocities diverge in the presence of ocean currents the path following behavior is degraded. Without correction for cross-currents (perpendicular to the desired path) the navigation path stabilizes to a parallel offset from the desired path.

As the operations of the UI AUVs are extended to ocean environments, the heading controller must be able to counteract the effects of significant water currents. Thus to achieve path following behavior in the ocean environments, the heading controller has been modified to use the EKF estimates of east and north currents as offset parameters in the MOOS heading controller. As accurately following the waypoint path is of more importance than reaching a position along the path at a specified time, only the effects of perpendicular current is considered.

The effects of perpendicular current are calculated by projecting the water current, as a vector, along the perpendicular direction to the path. Using the estimate of the AUV's VTW and this perpendicular current estimate, a corrected desired heading (ψ_d) can be calculated based on the relative magnitudes (see Fig. 2). This compensated heading sets the AUVs effective heading to match with the previously calculated MOOS heading.

D. *Simulation*

For the proposed approach to navigation in the presence of ocean currents, a kinematic simulation was conducted using MATLAB (software from 'The MathWorks'). The simulation propagates a true state as well as the EKF estimate, using the true state to create measurements coupled with noise. These measurements reflect AUV real-time operations, with a speed and heading measurement every quarter seconds and 4 range measurements, one from each transponder in the LBL array, every 2 seconds. Navigation uses only the EKF estimates, as the simulated true state would not be available during AUV missions. During the simulation, the AUV navigates at a speed of 0.85 m/s clockwise around a 50x100 m rectangular waypoint course starting near the northwest waypoint. Using the covariance matrices presented above and constant currents: -0.4 m/s and 0.1 m/s in the east and north directions, respectively, the estimation error and the perpendicular error (error perpendicular to path) were recorded. This simulation was conducted with the unmodified MOOS heading controller

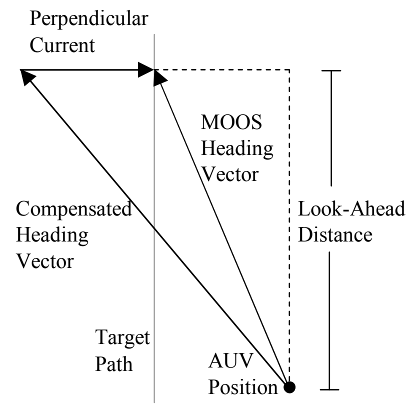

Fig. 2. Calculation of the water-current compensated heading vector for the modified MOOS heading controller.

as well as with the perpendicular-current compensated MOOS heading controller.

III. RESULTS

Simulation results show consistent convergence of the EKF estimate and the true state for both modified and unmodified controllers (shown in Fig. 3-4). Because the state covariance matrix P in the EKF is initialized with large values relative to their expected magnitudes, the initial state estimate is poor. The large jumps during this transient period correspond to the occurrence of range measurements. After several measurement cycles, the EKF estimate stabilizes and begins tracking the true north and east position more accurately. As can be seen in Fig. 3 (middle) and Fig. 4 (middle), the mean position estimation error for the EKF estimate over the entire run is approximately 1.06 m; if you ignore the transient period (first 50 m) this error reduces to ~0.86 m. These plots also show that the EKF estimate does not degrade during changes to the AUV desired heading.

The simulation was conducted with both the unmodified MOOS heading controller and the current compensated MOOS heading controller. Both of these simulation cases use the EKF estimate as the controller parameters to determine navigation. In both Fig. 3 (top) and Fig. 4 (top) the target path is shown as a grey line with the waypoints at each corner shown as a small grey circle. When the AUV gets within a 5m radius of a waypoint, it transitions to navigating towards then next waypoint. This transition can be observed both when the AUV begins to turn in Fig. 3 (top) and Fig. 4 (top) before reaching the corner and in Fig. 3 (bottom) and Fig. 4 (bottom) with the off-path error spiking when the target waypoint switches.

As can be seen in Fig. 3 (top), the unmodified MOOS heading controller drives the AUV along a path nearly parallel to the target path. The offset of this parallel path corresponds to a steady state solution of the MOOS heading controller against the magnitude of perpendicular current. This is shown clearly in Fig. 3 (bottom) where there is a significant offset when travelling in the north and south directions, corresponding to higher perpendicular current, and only a slight offset in the paths when driving in the east and west directions.

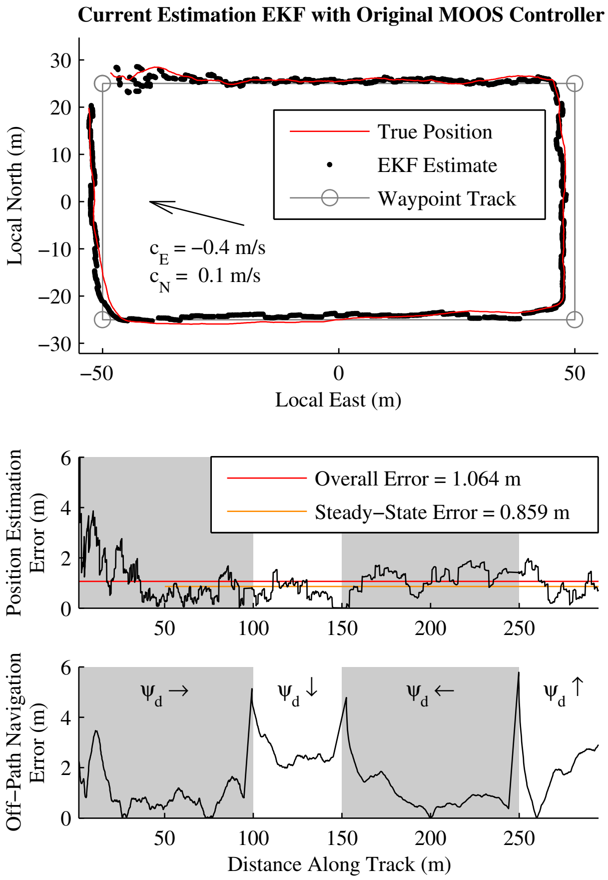

Fig. 3. Estimation and navigation performance with current estimation EKF and original MOOS controller. Top plot shows waypoint tracking performance showing true position (solid red line) and EKF estimate (black dots). The arrow indicates the direction and magnitude of the simulated current, which clearly causes a navigational offset. Middle plot shows EKF estimation error as the AUV travels the waypoint track. Bottom plot shows the navigation error as the AUV travels the waypoint track.

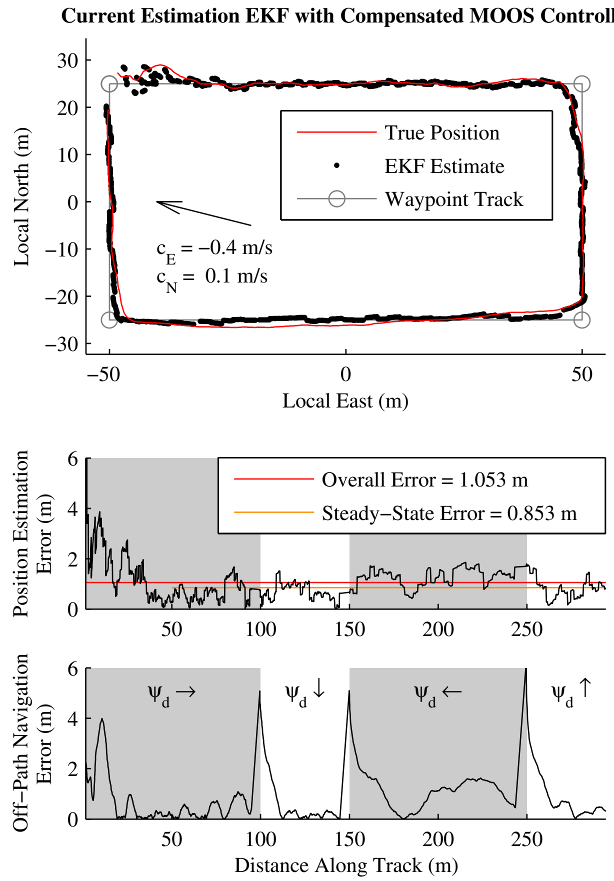

Fig. 4. Estimation and navigation performance with current estimation EKF and modified MOOS controller. Top plot shows waypoint tracking performance showing true position (solid red line) and EKF estimate (black dots). The arrow indicates the direction and magnitude of the simulated current, which is not noticeable in the navigational performance. Middle plot shows EKF estimation error as the AUV travels the waypoint track, which is similar to that shown in Fig. 3. Bottom plot shows the navigation error as the AUV travels the waypoint track, which is significantly smaller than shown in Fig. 3.

When the modification to the MOOS heading controller is implemented, the desired heading is modified when necessary to counteract perpendicular (cross) currents. As can be seen in Fig. 4 (top) and Fig. 4 (bottom), the current compensated MOOS heading controller follows the target path much closer than the unmodified version.

IV. Discussion and Conclusions

This paper presented a novel approach to state estimation and navigation for overcoming ocean currents. The results from simulation are promising. The ocean current estimation EKF is able to accurately estimate currents in simulation and use these estimated currents to better estimate its other states. This EKF estimate does take time to converge to the true state, but once converged maintains an accurate state estimation even when changing directions in the presence of currents. Using this ocean current estimation EKF with the current compensated MOOS heading controller improves navigation in the presence of currents and is able to drive the AUV along a target path.

With further field testing, better covariance estimates for the EKF matrices can be achieved. This will improve the EKF estimate and, with this improved state estimate, improve navigation in the presence of currents. The results of the simulation provide a first step towards real-world implementation and evaluation of this state estimation and navigational approach for the fleet of AUVs at UI.

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