AUV Navigation in the Presence of a Magnetic Disturbance with an Extended Kalman Filter

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Abstract- **This paper presents a novel extended Kalman filter (EKF) used for navigation of an autonomous underwater vehicle (AUV). The AUV contains a magnetic compass, which is susceptible to magnetic disturbances, and an angular velocity sensor, which exhibits drift if solely integrated to estimate heading. To address these problems, the presented EKF fuses the information from these sensors in order to produce a more accurate estimate of heading, and learns a heading bias in real-time. The presented method has two distinct advantages. First, the heading bias can correct for errors from a poorly calibrated magnetic heading sensor. Second, the angular velocity information improves heading estimation, especially in the presence of a magnetic disturbance. Because the AUVs presented here are designed to acquire magnetic field measurements, this second advantage is of particular importance. In both simulation and experimental testing, the presented EKF learned a calibration bias for the magnetic heading sensor and improved heading estimation in the presence of a magnetic disturbance.**

I. Introduction

The Center for Intelligent Systems Research (CISR) at the University of Idaho is developing a fleet of autonomous underwater vehicles (AUVs) to measure the magnetic fields near US naval vessels [1, 2]. By combining the magnetic measurements from all of the AUV's in the fleet, the magnetic signature of the vessel may be determined. The measurements will be used to reduce the magnetic signature of the vessel through active cancelation [3]. This makes the vessels less susceptible to undersea mines, which are the largest threat to navy ships post World War II [4].

To obtain these magnetic measurements, it is important that each AUV in the fleet is able to accurately navigate with respect to the naval vessel reference frame. The previously reported implementation [1] of the onboard navigation extended Kalman Filter (EKF) for each AUV utilizes acoustic ranges from four fixed transponders at known locations, propeller RPM correlated speed measurements, and a heading measurement from the onboard magnetic compass. The EFK was developed to fuse these measurements into an estimate of the position (north and east), orientation (heading), and velocity (linear speed) of the AUV (for details see [1]).

One problem with this approach is that it relies on a heading sensor that is based on a measurement of Earth's magnetic field. These sensors perform well when properly calibrated and magnetically undisturbed. However, these AUV's are being developed in order to measure the magnetic field surrounding naval vessels. The magnetic heading sensor on the AUV's are unable to differentiate between the Earth's magnetic field and the induced magnetic field of the naval vessel, and thus may falsely interpret the change in magnetic field as a change in vehicle heading. Therefore it is important that the onboard navigation system maintain an accurate heading estimate in the presence of the magnetic field disturbance caused by a naval vessel.

In addition to the measurements previously mentioned, the AUV's also contain an inertial measurement unit (IMU) that provides 3-axis linear accelerations and 3-axis angular velocity measurements. The angular velocities measured by the IMU may be mapped to the angular heading rate using the onboard pitch and roll sensors. This gives a measurement of the time rate of change of AUV heading, providing new information about the heading of the AUV without using a magnetically based measurement.

This paper describes an onboard navigation EKF that combines acoustic range data, an AUV speed measurement, heading measurement, and angular velocity measurement in order to produce a more accurate estimate of the position (north and east), orientation (heading), and velocity (linear speed) of the AUV. This novel approach also includes a state for heading bias, which is learned in real-time. This heading bias can correct for calibration errors in the magnetic heading sensor. The main advantage, however, is from the angular velocity sensor, which improves heading estimation, especially in the presence of a magnetic disturbance which causes a direct deflection in the magnetically based heading sensor.

Previous work has addressed the problem of estimating the state of an underwater vehicle, including [1, 5-11] and others. In [5], heuristic fuzzy filtering is used to combine sensor information to estimate state. In order to prevent estimation instabilities, the measurement covariance matrix is optimally adjusted in [6, 7] based on the error between predicted and measured states. An alternate approach for adjusting the measurement covariance matrix is presented in [8]. In [9], an inertial rate sensor is added to improve state estimation of heading. These previous approaches do not include an estimate of a heading bias.

Alternate approaches that learn a heading bias have been developed previously by [10, 11] and others. In both [10] and [11], the heading bias is learned by using GPS or DGPS measurements as references. This approach is limited to the availability of the position measurements provided by GPS, which is limited in frequency during underwater magnetic measurement missions. The approach presented in this paper, however, combines low rate positional measurements in the form of the acoustic ranges with higher rate angular velocity measurements from the IMU. This addition of angular velocity measurement is critical for heading estimation during the gaps between acoustic range data.

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This paper presents both simulated and experimental data showing the efficacy of the presented approach. All experimental navigation data is compared to a ground truth produced by an accurate floor-mounted acoustic topside tracking system. The first set of tests demonstrates the ability of the EKF to correct for a poorly calibrated compass. In these tests, the EKF successfully learned a compass bias in order to correct for the poor calibration. A second set of tests show the response of the EKF in the presence of a magnetic disturbance. These tests use data collected near a fixed magnetic source and near a small ferrous barge. Because the magnetic sensor assumes the Earth's magnetic field is fixed the sensor falsely interprets the source as a change in heading. These experiments demonstrate that the EKF is able to mitigate a compass deflection caused by the presence of a magnetic disturbance.

II. Methods

The following sections describe the autonomous underwater vehicles, sensors and related hardware, and the extended Kalman filter used for state estimation as part of the onboard navigation system.

A. *Autonomous Underwater Vehicles (AUVs)*

The AUVs for which the presented EKF have been developed are shown in Fig 1. The AUVs are modified versions of the vehicles developed by Dan Stillwell at Virginia Polytechnic Institute, and are approximately 1m long and 10cm in diameter. Each AUV is controlled by a distributed processor network of 5 microcontrollers [12]. The AUVs use classical proportional controllers to follow a set of waypoints, with heading and depth controlled separately. The heading controller for the AUVs uses simple proportional feedback to adjusted the vehicles heading towards a desired heading (for details, see [1]). The controller used for heading navigation is based on the state estimation from the onboard EKF. The EKF performs states estimation based on information from the onboard AUV sensor hardware, which is described in the following section.

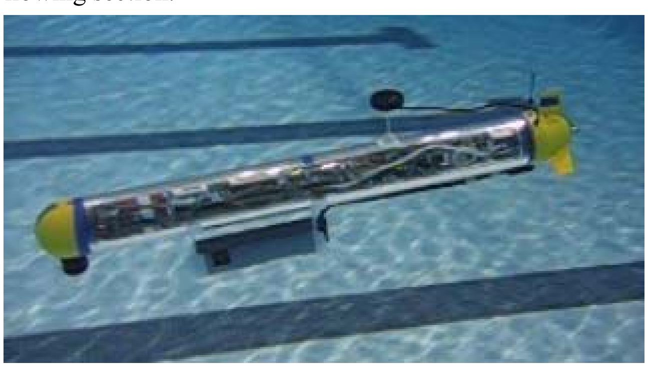

Figure 1. A single AUV of the fleet under development at the University of Idaho.

B. *AUV Sensor Hardware*

Each AUV is equipped with an arrangement of sensors for measuring various attributes of its state. Heading of the AUV is measured with a magnetic compass utilizing magnetoresistance technology and capable of an accuracy of ±0.5° when properly calibrated. An inertial measurement unit (IMU, Archangel Systems INC, model IM3-C1-2) with solid state MEMS accelerometers and gyroscopes provides angular velocities and linear accelerations for three orthogonal axes with accuracies of 0.15°/sec and 10milli-*g*, respectively. Pitch and roll measurements are calculated using two micro-electro-mechanical (MEMS) accelerometers. These measurements are used to map angular velocity from the IMU inertial frame to the EKF fixed reference frame. Acoustic ranges are calculated using time-of-flight measurements to transponders at known locations. The time-of-flight measurements are acquired using an acoustic Micro-modem developed by Woods Hole Oceanographic Institute. Each AUV is also equipped with a capacitive type pressure sensor to calculate depth to an accuracy of ±0.0879m. For additional sensor and hardware information see [1].

To reduce computational expense, the navigation EKF uses a reduced subset of the information provided by the onboard sensors. The sensors used in the EKF, and the EKF system and measurement model, are described in the section below.

C. *Extended Kalman Filter with Heading Bias*

The onboard navigation system uses the EKF to estimate the position (North and East), speed, and heading of the AUV. The EKF also estimates a heading bias. The onboard navigation system also uses pitch, roll, and depth measurements as part of the controller feedback, but these states are not estimated by the EKF.

The system propagation model for the extended Kalman filter (EKF) follows the standard form [13]:

$$X_k = f(X_{k-1}, u_k, w_k), \tag{1}$$

where X_k is the system state, f is the nonlinear difference equation, u_k is the driving function, and w_k is the zero-mean process noise. The EKF updates with an observation model

$$y_k = h(X_k, v_k), \tag{2}$$

where v_k is the zero-mean measurement noise and h is the nonlinear measurement equation that relates the system state X_k to the measurement y_k.

The presented approach adds a heading bias, b, to the system state previously reported in [1]. The expanded onboard navigation EKF for the AUV has the system state vector:

$$X = \{N \quad E \quad s \quad \psi \quad b\}^T. \tag{3}$$

where N and E are the positions in the North and East directions, respectively, s is the speed, and ψ is the heading. In addition to adding a heading bias state, the presented approach adds a calculated time rate of change of heading, $\dot{\psi}_m$, as a driving function in the EKF. The discrete time system model for the EKF is now defined as:

$$X_k = f(X_{k-1}, u_k, w_k) = \begin{Bmatrix} \Delta t\ s\ cos\psi + N + w_E \\ \Delta t\ s\ sin\psi + E + w_N \\ s + w_s \\ \Delta t\dot{\psi}_m + \psi + w_\psi \\ b + w_b \end{Bmatrix}_{k-1}, \tag{4}$$

where Δt is the discrete time step, and the w's are the process noise. To calculate $\dot{\psi}_m$, the three measured angular rates, ω_x,

ω_y, and ω_z from the IMU are transformed into Euler angle rates $\dot{\phi}$, $\dot{\theta}$, and $\dot{\psi}$ using [19]

$$\begin{Bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{Bmatrix} = R_\omega \begin{Bmatrix} \omega_x + w_{\omega_x} \\ \omega_y + w_{\omega_y} \\ \omega_z + w_{\omega_z} \end{Bmatrix}, \quad (5)$$

where

$$R_\omega = \begin{Bmatrix} 1 & sin\phi tan\theta & sin\phi tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi sec\theta & cos\phi sec\theta \end{Bmatrix} \quad (6)$$

is the non-orthogonal transformation as a function of Euler angles ϕ, θ, and ψ corresponding to roll, pitch, and heading, respectively. The time rate of change of heading, $\dot{\psi}_m$, is used as the driving function in the system model, but the angular rates for roll, $\dot{\phi}$, and pitch, $\dot{\theta}$, are not used by the onboard navigation EKF.

The measurements used for EKF correction are:

$$y_k = \{r_1 \quad r_2 \quad r_3 \quad r_4 \quad s_m \quad \psi_m\}^T, \quad (6)$$

where $r_{1\text{-}4}$ are acoustic ranges to fixed transponders at known locations, the speed s_m is calculated from propeller RPM using a linear fit, and ψ_m is the measured compass heading. The measurements were related to the states using

$$y_k = \begin{Bmatrix} \sqrt{(N - B_{N1})^2 + (E - B_{E1})^2 + (Z - B_{Z1})^2} + v_{r1} \\ \sqrt{(N - B_{N2})^2 + (E - B_{E2})^2 + (Z - B_{Z2})^2} + v_{r2} \\ \sqrt{(N - B_{N3})^2 + (E - B_{E3})^2 + (Z - B_{Z3})^2} + v_{r3} \\ \sqrt{(N - B_{N4})^2 + (E - B_{E4})^2 + (Z - B_{Z4})^2} + v_{r4} \\ s + v_s \\ \psi + b + v_\psi \end{Bmatrix}_k, \quad (7)$$

where B_N, B_E, and B_Z were the North position, East position, and depth of the transponders, respectively, Z is the depth measurement from the pressure sensor, and the v's are the measurement noises.

The state and error covariance are predicted and corrected with measurements using the standard method described in [13]. In this application, the EKF propagates and updates at a rate of 4 Hz with compass, heading, and speed measurements. The range measurements are updated at 2 second intervals. During the 2 second gap between range measurements, the EKF must rely on the heading sensor and angular velocity measurements to estimate heading.

III. Results

The following sections discuss the performance results of the presented EKF in both simulation and field testing. Simulations were carried out by applying the EKF to previously collected test data. This allows realistic inputs to the EKF but does not allow the coupling of the AUV controller and EKF to be determined. Therefore it was necessary to collect field testing with the EKF embedded on the AUV.

A. Topside Tracking

The AUVs were tested at the Acoustic Research Detachment, which is part of the Naval Surface Warfare Center, Carderock Division. The facility is located on the south end of Lake Pend Oreille and covers approximately 23,000 square meters. The average depth of the test range is 15 meters.

The test range is equipped with a topside tracking system which utilizes four bottom-mounted tracking nodes. This system provides a position reference which can be used to evaluate the AUV navigation performance. The tracking nodes are also used as the transponders for the EKF Long Baseline (LBL) ranging.

Tests conducted show that the topside tracking range is capable of position accuracies of approximately 0.01m. However with the ranging ping used on the AUV, the accuracy is reduced to approximately 0.1m. Because no direct measure of the true AUV heading is available, the discrepancy between the topside tracking system position and the EKF position estimate acts as the performance metric. The topside tracking system provides a position with each LBL range, which occurs on a 2 second cycle.

B. Calibration Correction

The initial test for the presented approach was simulation of an artificial compass bias. A simple bench test was performed to determine an appropriate compass bias. The test was conducted by placing a permanent magnet near the AUV. The magnet was positioned such that it created a magnetic field change in the on-board magnetometer similar to the expected field of a naval vessel. This magnetic disturbance typically caused a compass deflection of 3-5 degrees depending on the magnet location and orientation. Using this result, a 5 degree compass bias was artificially added to previously collected test data. Fig. 2 below shows the results of the simulation.

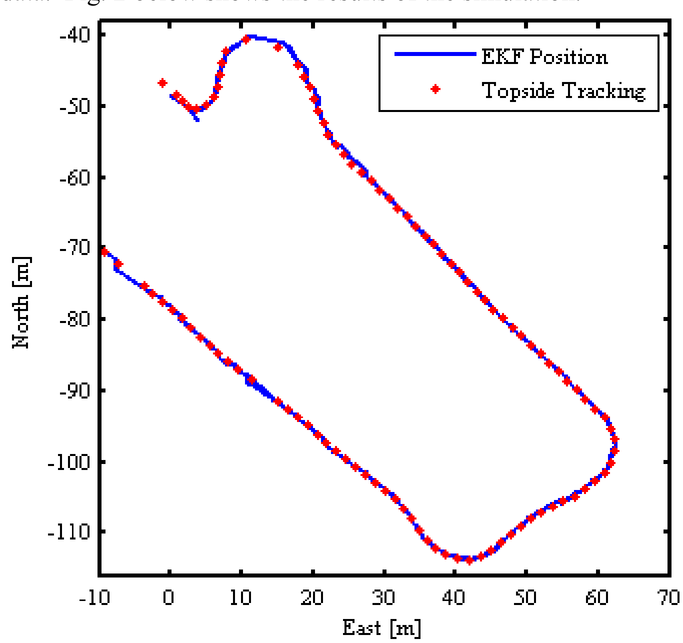

Figure 2. Simulation result for artificially adding a 5 degree compass bias to past field test data.

Fig. 2 above compares the topside tracking to the position estimated by the EKF. The EKF position estimation results closely match the topside tracking solutions. The EKF actually improved the position estimation of the AUV even with the added artificial bias. This is because the EKF could account for a compass bias in the field test data which was previously unaccounted for. Fig. 3 below shows the compass heading and EKF heading collected from the same simulation. This figure shows the difference between the compass reading and the heading estimated by the EKF, and it is clear that the EKF properly learned the superimposed 5 degree compass bias.

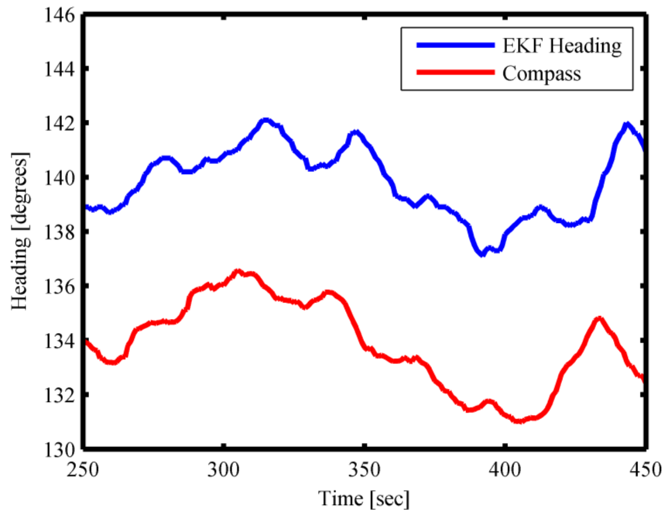

Figure 3. Simulation result for artificially adding a 5 degree compass bias to past field test data. Plot shows the bias compass heading compared to the EKF heading, which clearly identifies and removes the bias.

The next test for the EKF was an AUV field test. The AUV compass was mis-calibrated by approximately 3 degrees. Fig. 4 shows the results of the test. Like the simulation test, the EKF was able to perform well. The EKF even outperformed previous tests with a properly calibrated compass (see [1] for previous results). The average distance error in estimated position was 60cm compared with the topside tracking position.

C. Magnetic Disturbance Rejection

The next simulation tested the performance of the presented EKF in the presence of a magnetic disturbance. The simulation used data collected during a fixed magnetic source field test. The AUV's path took it in close proximity to a magnetic source. Because the magnetic sensor assumes the Earth's magnetic field is fixed, the sensor falsely interpreted the source as a change in heading. The magnetic source, though only creating an impulse effect on the compass, caused a deflection approximately the same magnitude as could be expected from a naval vessel. Fig. 5 shows the data collected and compares the compass measurement with a direct Euler integration of the angular rate gyro. The EKF effectively combines the two measurements to minimize both the magnetic disturbance and any angular rate gyro integration biases in the estimated heading. The result is a more accurate estimate of heading in the presence of the magnetic disturbance.

The final test was an AUV field test with the EKF under a ferrous barge. The AUV's waypoint course took it under the center of the small barge. The barge was approximately a 30'x15'x4' metal vessel which was securely anchored in the test range. Fig. 6 shows the position of the barge relative to the

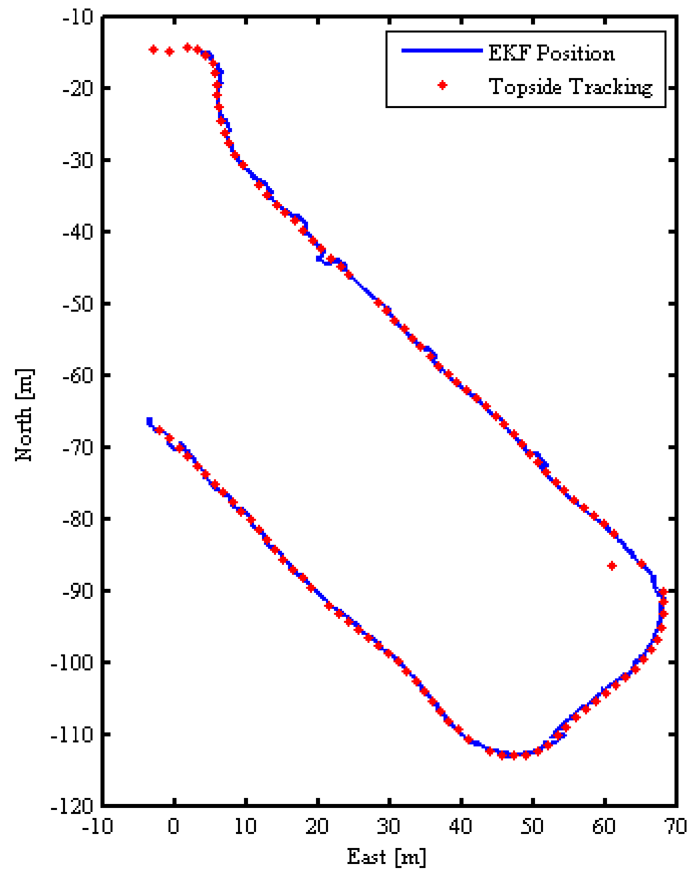

Figure 4. Field test data of mis-calibrated compass. The effect of the compass bias is clearly accounted for by the EKF, which accurately estiamtes the position of the AUV in comparison to the topside tracking.

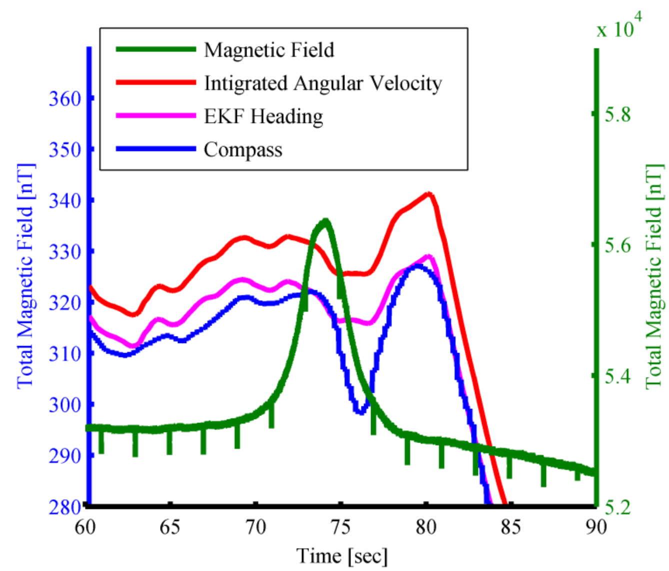

Figure 5. Simulation test of the EKF in the presence of a magnetic source. The plot compares the compass measurement, a directly integrated angular velocity sensor, and the EKF estimated heading. The spikes in the magnetic field are due to the outgoing acoustic navigation ping and do not have a noticeable effect on the compass.

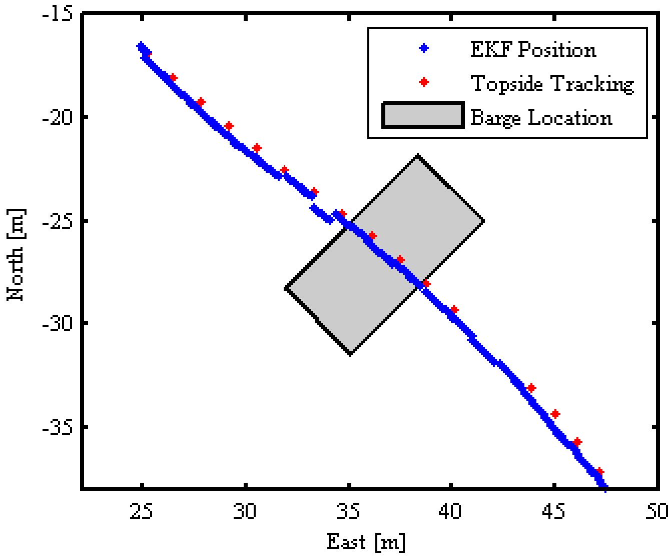

Figure 6. Field test of the EKF under a ferrous barge. The path of the AUV passes directly under the barge.

AUV's path. The AUV's depth was 1.8m which took it about 1.2m below the barge. Tests conducted at full beams depth, 5m, found that the magnetic disturbance and compass deviation created was negligible.

Fig. 7 below shows the magnetic field and compass measurements produced by the barge plotted against the EKF heading estimated by the AUV during the test. The disturbance event lasted almost 15 seconds and produced a large magnetic disturbance and compass deflection. The compass deflection, which was nearly 20 degrees, was considerably larger than the previous results of 3-5 degrees, primarily due to the AUV's depth being less than beams depth. Even so, Fig. 7 shows that the EKF heading estimate is not adversely affected by the magnetic disturbance.

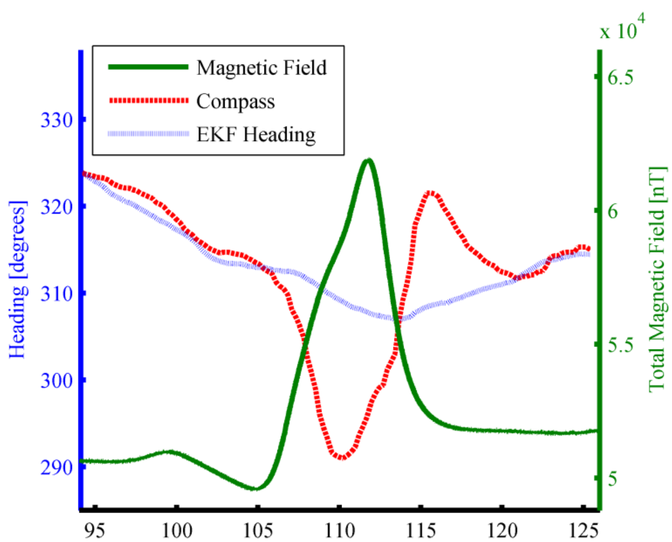

Figure 7. Field test of the EKF under a ferrous barge. The compass is clearly effected by the magnetic disturbance, but the EKF heading is able to disregard the erronious sensor information.

IV. Discussion and Conclusion

This paper describes an extended Kalman filter that is able to accurately estimate heading in the present of a magnetic disturbance. The EKF includes a compass bias state and a heading angular rate driving function which allows it to correct for poor compass calibration and to reject compass deflections caused by the presence of magnetic disturbances. Previous work has neither accounted for bias in the heading measurement nor temporary compass deflection that can be expected when navigating in a magnetic disturbance.

In magnetic signature measurement missions, the AUV fleet depth prevents the use of position data from GPS. In the approach presented here, the EKF leverages measurements of heading angular velocity and acoustic LBL ranging to effectively disregard heading bias and to navigate in the presence of a magnetic disturbance.

The presented simulation and field testing has shown that the EKF removes errors caused by a poorly calibrated compass. In addition, field tests have shown a position accuracy of 60cm when the heading compass was poorly calibrated. Additional testing demonstrated the performance of the EKF in the presence of a magnetic disturbance. In an impulse disturbance test, the EKF successfully estimated heading during a compass deflection caused by magnetic source. In order to test the response of the EKF to a longer disturbance, field test were conducted under a small ferrous barge which produced large compass deflections (near 20 degrees). This test showed that the EKF is able to successfully estimate heading and navigate in the presence of a magnetic disturbance.

Acknowledgment

The authors gratefully acknowledge the support of the Office of Naval Research, through "Electromagnetic Signature Assessment System Using Multiple Autonomous Underwater Vehicles (AUVs)", ONR N00014-08-1-0779.

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