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Improving Aiding techniques for USBL Tightly-Coupled Inertial Navigation System

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Abstract: This paper presents two Tightly-Coupled fusion techniques to enhance position, velocity and attitude estimation based on position fixes of an Ultra-Short Base Line (USBL) positioning system with low update rates and the high rate Inertial Navigation System (INS) outputs, subject to bias and unbounded drift. In this framework, the vehicle interrogates transponders placed at known positions of the mission scenario to obtain a measure of distance and attitude of the vehicle relatively to the transponders. Whereas the travel time of the acoustic signals from the transponder to the vehicle is commonly approximated in the literature by half of the Round Trip Time (RTT), a method that exploits the full RTT is presented taking into account the interrogation instant estimates and the associated uncertainty. The relevance of the inclusion of the interrogation instant information and the enhanced performance outcome from the proposed techniques are assessed in Monte Carlo simulations of the overall navigation system.

1. INTRODUCTION

In recent years, low-cost Inertial Navigation Systems (INS) stepped forward as a significant aid for Underwater Vehicles (UV) navigation in the fulfillment of several missions at sea. The execution of these tasks, that include environmental monitoring, surveillance, underwater inspection of estuaries, harbors, and pipelines, and geological and biological surveys (see Pascoal et al. [2000]), requires low-cost, compact, high performance, and robust navigation systems that can accurately estimate the UV position and attitude. The average INS yields excellent short-term accuracy, however, long term position drifts arise due to the integration of non-ideal inertial sensors bias and noise, if not compensated by aiding sensors.

Among several available underwater navigation aiding sensors such as Doppler Velocity Loggers (DVL), depth pressure sensors, and magnetic compasses, acoustic positioning systems (see Milne [1983], and Vickery [1998]) like Long Base Line (LBL), Short Base Line (SBL), and Ultra-Short Base Line (USBL) stand often as the primary choice for underwater positioning (see Lurton and Millard [1994], Smith and Kronen [1997], Larsen [2000], and Lee et al. [2004]).

In the proposed mission scenarios, illustrated in Fig. 1, the vehicle is equipped with an INS and an USBL array, in an inverted USBL configuration (Vickery [1998]), that interrogates transponders located in known positions of the mission area, engaging in interrogations over considerable distances, ranging typically from a few meters to several kilometers. An alternative configuration, in which the USBL array is installed on-board a surface support ship, was adopted in Steinke and Buckham [2005].

In generic operating conditions, a CTD (Conductivity, Temperature and Depth) profile is normally required to account for the underwater sound velocity variations. Inverted USBL configurations, besides paving the way to future fully autonomous systems without the need to have surface mission support vessels, allows for the sound velocity to be considered constant while operating in the same underwater layer as the transponders (for instance, bottom operation while interrogating bottom placed transponders).

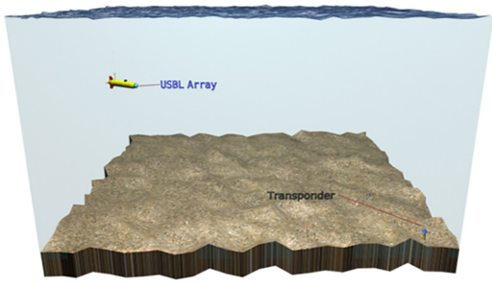

Fig. 1. Mission scenario

Considering the typical distances in the mission scenarios, the velocity of acoustic waves in underwater environments cannot be neglected and leads to a significant time lag between the interrogation and the reception of the reply from the transponder. Consequently, the vehicle position and attitude at the interrogation instant and at the reception of the reply from the transponder might be significantly

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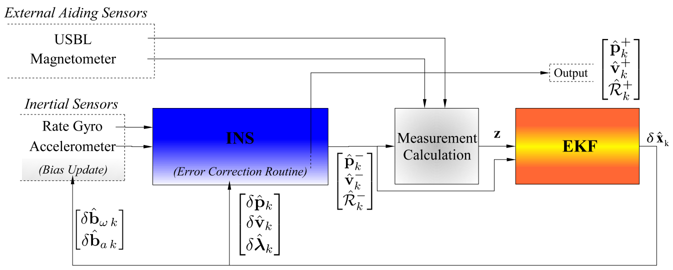

Fig. 2. Navigation system block diagram

different. Classical USBL positioning schemes compute the travel times from the transponders to the receivers mounted on the vehicle, based on half of the Round Trip Time (RTT) of signals sent on an interrogation event and replied by the transponders. A method of accounting for the vehicle motion during the interrogation-reply time lag was proposed in Lee et al. [2004] by including range bias in the filter states to suppress the undesired relative movement effect.

This paper focuses on enhancing the performance and robustness of the coupling between the USBL and the INS, bringing up filtering techniques that allow for the inclusion of stochastic information about the system estimates on the instant of interrogation, and exploiting the information of the full elapsed RTT of the acoustic signals.

Previous work from the authors include a vehicle dynamics aiding technique integrated with an INS/USBL architecture, that was successfully adopted in Morgado et al. [2007], yielding unique data that provides a comprehensive set of observations of the inertial system errors, and further enhancing the performance of the overall navigation system.

The paper is organized as follows: the main aspects of the navigation system and the proposed architecture are briefly reviewed in Section 2. Section 3 describes the USBL system and the transponder interrogation and reply scheme. The proposed techniques to fuse the USBL information with the INS are brought to full detail in Section 4. Simulation results of the overall navigation system are presented in Section 5. Finally, Section 6 draws some concluding remarks and comments on future work.

2. NAVIGATION SYSTEM ARCHITECTURE

The proposed navigation system architecture is depicted in Fig. 2. The INS is the backbone algorithm (Savage [1998a,b]) that performs attitude, velocity and position numerical integration from rate gyro and accelerometer triads data, rigidly mounted on the vehicle structure (strapdown configuration). The undesirable INS estimates drift, due to integration of non ideal inertial sensor disturbances (bias and noise), is dynamically compensated by the EKF that estimates position, velocity, attitude and bias compensation errors, according to the direct-feedback configuration shown in Fig. 2.

The inputs provided to the inertial algorithms are the accelerometer and rate gyro readings, corrupted by zero mean white Gaussian noise $\mathbf{n}$ and random walk bias, $\dot{\mathbf{b}} = \mathbf{n}_b$, yielding

$$^B\mathbf{a}_{SF} = ^B\bar{\mathbf{a}} + ^B\bar{\mathbf{g}} - \delta\mathbf{b}_a + \mathbf{n}_a, \quad \boldsymbol{\omega} = \bar{\boldsymbol{\omega}} - \delta\mathbf{b}_\omega + \mathbf{n}_\omega$$

where $\delta\mathbf{b} = \mathbf{b} - \bar{\mathbf{b}}$ denotes bias compensation error, $\bar{\mathbf{b}}$ is the nominal bias, $\mathbf{b}$ is the compensated bias, $^B\bar{\mathbf{g}}$ is the nominal gravity vector, and the subscripts a and ω identify accelerometer and rate gyro quantities, respectively. For further details on the INS algorithm adopted in this work, see Morgado et al. [2006] and references therein.

The EKF error equations, based on perturbational rigid body kinematics, were brought to full detail by Britting [1971], and are applied to local navigation by modeling the position, velocity, attitude and bias compensation errors dynamics

$$\begin{aligned}
\delta\dot{\mathbf{p}} &= \delta\mathbf{v} \\
\delta\dot{\mathbf{v}} &= -\mathcal{R}\delta\mathbf{b}_a - [\mathcal{R}^B\mathbf{a}_{SF}\times]\delta\boldsymbol{\lambda} + \mathcal{R}\mathbf{n}_a \\
\delta\dot{\boldsymbol{\lambda}} &= -\mathcal{R}\delta\mathbf{b}_\omega + \mathcal{R}\mathbf{n}_\omega \\
\delta\dot{\mathbf{b}}_a &= -\mathbf{n}_{b_a} \\
\delta\dot{\mathbf{b}}_\omega &= -\mathbf{n}_{b_\omega}
\end{aligned} \tag{1}$$

respectively, where matrix $\mathcal{R}$ is the shorthand notation for Body to Earth coordinate frames rotation matrix, $^E_B\mathbf{R}$, and the attitude error rotation vector $\delta\boldsymbol{\lambda}$ is defined by $\mathbf{R}(\delta\boldsymbol{\lambda}) = \mathcal{R}\bar{\mathcal{R}}^T$, bearing a first order approximation

$$\mathbf{R}(\delta\boldsymbol{\lambda}) \simeq \mathbf{I}_{3\times3} + [\delta\boldsymbol{\lambda}\times] \Rightarrow [\delta\boldsymbol{\lambda}\times] \simeq \mathcal{R}\bar{\mathcal{R}}^T - \mathbf{I}_{3\times3} \tag{2}$$

of the Direction Cosine Matrix (DCM) parametrization, where $\bar{\mathcal{R}}$ represents nominal rotation matrix. The linear velocity and position errors are defined by

$$\delta\mathbf{v} = \mathbf{v} - \bar{\mathbf{v}} \ , \ \delta\mathbf{p} = \mathbf{p} - \bar{\mathbf{p}}, \tag{3}$$

respectively, where $\bar{\mathbf{p}}$ is Body frame origin position relative to the Earth coordinate frame, $\mathbf{p}$ the Body frame origin position estimate, $\bar{\mathbf{v}}$ is the nominal linear velocity, and $\mathbf{v}$ the linear velocity estimate.

The EKF error estimates are fed into the INS error correction routines as depicted in Fig. 2. The INS attitude estimate, $\mathcal{R}_k^-$, is compensated using the rotation error matrix $\mathbf{R}(\delta\boldsymbol{\lambda})$ definition, which yields

$$\mathcal{R}_k^+ = \mathbf{R}_k^T(\delta\hat{\boldsymbol{\lambda}}_k)\mathcal{R}_k^-$$

where $\mathbf{R}_k^T(\delta\hat{\boldsymbol{\lambda}}_k)$ is parameterized by the rotation vector $\delta\hat{\boldsymbol{\lambda}}_k$ according to the DCM form. The remaining state variables are linearly compensated using

$$\begin{aligned}
\mathbf{p}_k^+ &= \mathbf{p}_k^- - \delta\hat{\mathbf{p}}_k \quad , \quad \mathbf{v}_k^+ = \mathbf{v}_k^- - \delta\hat{\mathbf{v}}_k \\
\mathbf{b}_{a\ k}^+ &= \mathbf{b}_{a\ k}^- - \delta\hat{\mathbf{b}}_{a\ k} \ , \ \mathbf{b}_{\omega\ k}^+ = \mathbf{b}_{\omega\ k}^- - \delta\hat{\mathbf{b}}_{\omega\ k}
\end{aligned}$$

After the error correction procedure is completed, the EKF error estimates are reset maintaining the filter linearization assumptions valid.

3. USBL SYSTEM

The USBL sensor consists of a small and compact array of acoustic transducers that allows for the computation of a transponder position in the vehicle coordinate frame, based on the travel time of acoustic signals emitted by the transponder (see Milne [1983]). This travel time is obtained from the RTT of travel of acoustic signals from the pinger installed on the vehicle to the transponder placed at a known position and back to the receivers on the USBL array. The USBL array can be, for instance, installed on the vehicle nose, as suggested in Fig. 3. One of the acoustic transducer works simultaneously as an interrogator and receiver (known as projectors), and the remaining transducers can be used as receivers only (known as hydrophones).

The transponder interrogation and reply scheme works as follows: the interrogator placed on the vehicle emits an

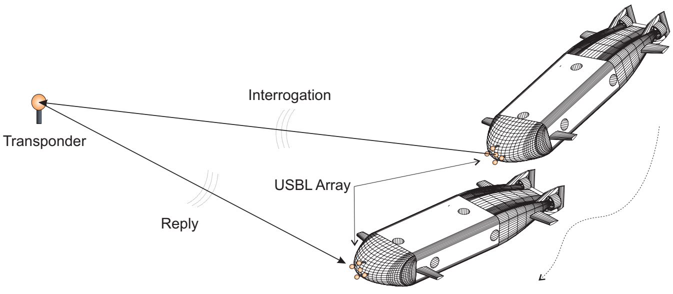

Fig. 3. USBL System Interrogation scheme

acoustic signal that travels at the speed of sound to the transponder and triggers a response from the transponder, with a known delay to allow for signal detection, that travels back to the USBL array installed on the vehicle. As depicted on Fig. 3, due to the considered distances and the relative velocities between the vehicle and the acoustic waves, the position of the vehicle at the instants of interrogation and reception is not the same. For instance, with typical UV velocities around 3 m/s, sound speed underwater around 1500 m/s and a distance of 1000 m between the vehicle and the transponder, the vehicle displacement is of about 4 m during the interrogation and response process.

Taking into account the quantization performed by the acoustic system, the RTT to each of the receivers on the USBL array is given

$$t_{i_{rtt}} = T_s \left[\frac{\bar{t}_p + \varepsilon_t}{T_s}\right] + \bar{t}_D + T_s \left[\frac{\bar{t}_{r_i} + \varepsilon_c}{T_s}\right] \qquad (4)$$

where $\bar{t}_p$ is the nominal travel time from the pinger on the vehicle to the transponder, $\bar{t}_{r_i}$ is the nominal travel time from the transponder to the ith acoustic receiver, T_s is the acoustic sampling period and $[\cdot]$ represents the mathematical *round* operator. The terms ε_t and ε_c represent respectively the noise at the transponder and at the receivers (common to all receivers - includes transponder-receiver relative motion time-scaling effects and errors in sound propagation velocity). The response delay time $\bar{t}_D$ is considered to be known, so it can be removed upon reception of the signals.

The measurements of transponder-receivers travel times is commonly obtained by dividing the RTT by two as suggested by Milne [1983], which neglects the movement of the vehicle during the round trip of the acoustic waves. It is then reasonable to consider, under the vehicle stationarity assumption, that the travel times between the transponder and the receivers can be computed by removing the known reply delay on the transponder and half of the RTT $t_{p_{rtt}}$ measured by the projector that interrogated the transponder

$$t_{r_i} = t_{i_{rtt}} - \bar{t}_D - \frac{1}{2}\left(t_{p_{rtt}} - \bar{t}_D\right) \qquad (5)$$

4. INS AIDING

This section describes the techniques used to aid the INS with the USBL sensor information. The first strategy consists of feeding the EKF with the computed transponder-receivers travel times (5), and based on a Tightly-Coupled solution proposed in Morgado et al. [2006]. The second strategy, presented in subsection 4.2, is directed toward the inclusion of the stochastic information about the filter state in the interrogation instant. Thus it takes into account the movement of the vehicle during the significant time lag that occurs between the interrogation and the reception of the reply, resorting to a state augmentation method.

4.1 Tightly-Coupled EKF

The tightly-coupled EKF formulation is based on measurements of the travel time between the transponder and the receivers on the USBL array, obtained from the RTT measurements resorting to (5). The travel time measurements are then considered to be approximately described by

$$z_{r_i} = \bar{t}_{r_i} + \eta_i \qquad (6)$$

where η_i represents the measurement noise for receiver i that corresponds essentially to the quantization error induced by the acoustic system sampling frequency and the digital implementation of the detection algorithms. This measurement noise also encompasses errors inherent to the relative movement between the transponder and the vehicle, that is not explicitly modeled in this formulation. Due to the considerable displacement of the vehicle during the RTT of the acoustic signals, this strategy leads to biased position estimates in certain transponder-vehicle relative movement configurations.

Although the arrival times at each of the receivers is different, the measurements are all fed to the filter at the same instant due to the extremely close proximity of the receivers on a USBL array (the vehicle displacement between the arrival of the acoustic wave at the first receiver and the last is neglected). The travel time from the transponder to each receiver on the USBL array at the reception instant k_r is given by

$$\bar{t}_{r_i} = \| \, {}^{E}\bar{\mathbf{p}}_t - {}^{E}\bar{\mathbf{p}}_{r_i} \| / v_p = \| \, {}^{E}\bar{\mathbf{p}}_t - \bar{\mathbf{p}} - \bar{\mathcal{R}} \, {}^{B}\bar{\mathbf{p}}_{r_i} \| / v_p \qquad (7)$$

where ${}^{E}\bar{\mathbf{p}}_{r_i}$ and ${}^{B}\bar{\mathbf{p}}_{r_i}$ are the positions of receiver i, respectively, in Earth and Body coordinate frames, ${}^{E}\bar{\mathbf{p}}_t$ is the known position of the transponder in Earth coordinate frame, and v_p represents the acoustic waves velocity underwater, assumed constant and known.

Using the approximation for the attitude error (2) and the position error definition (3) in (7) yields (see Morgado et al. [2006])

$$\begin{aligned}\bar{t}_{r_i} \approx \| \, & {}^{E}\bar{\mathbf{p}}_t - \mathbf{p}_{k_r} + \delta\mathbf{p}_{k_r} \\ & - \mathcal{R}_{k_r} \, {}^{B}\bar{\mathbf{p}}_{r_i} - \left[\mathcal{R}_{k_r} \, {}^{B}\bar{\mathbf{p}}_{r_i} \times\right] \delta\boldsymbol{\lambda}_{k_r} \| / v_p \end{aligned} \qquad (8)$$

which are integrated into the EKF as observations for each receiver by linearizing $\bar{t}_{r_i}$ about the filter state space variables and the INS estimated quantities. The subscript k_r indexes the instant of reception of the acoustic reply from the transponder.

The EKF implements the discretized INS error model (1) with state vector given by

$$x_k = \left[\delta\mathbf{p}_k \;\, \delta\mathbf{v}_k \;\, \delta\boldsymbol{\lambda}_k \;\, \delta\mathbf{b}_{ak} \;\, \delta\mathbf{b}_{\boldsymbol{\omega}k}\right]^T \qquad (9)$$

The state estimate is updated using the standard EKF state update equation

$$\hat{x}_k = \hat{x}_k^- + K\left(z_k - h\left(\hat{x}_k^-\right)\right) \qquad (10)$$

where K is the EKF gain, $\hat{x}_k$ is the update state estimate, $\hat{x}_k^-$ is the prior state estimate, z_k are the transponder-receivers travel time observations, and $h\left(x_k^-\right)$ is the set of non-linear predicted observations for the receivers, evaluated at the prior state estimate using (8).

The remaining quantities are calculated using the standard EKF update and propagation equations (see Gelb [1974])

$$K = P_k^- H_k^T \left(H_k P_k^- H_k^T + R_k\right)^{-1} \tag{11}$$

$$P_k = (I - K H_k) P_k^-, \; P_{k+1}^- = \phi_k P_k \phi_k^T + Q_k \tag{12}$$

where P_k is the state estimation error covariance matrix, R_k is the observations noise covariance matrix, Q_k is the covariance matrix of the continuous state noise contribution from sample time t_k to t_{k+1}, H_k is the Jacobian matrix of the nonlinear observation equation $h\left(x_k^-\right)$ evaluated at the prior state estimate, and ϕ_k is the state transition matrix obtained by the discretization

$$\phi_k \approx e^{F_k (t_{k+1} - t_k)} \tag{13}$$

where F_k is the Jacobian of the INS error model (1) evaluated at the updated state estimate $\hat{x}_k$.

4.2 Interrogation State Augmentation EKF

The Interrogation State Augmentation EKF formulation takes into account the estimation errors of the interrogation instant and the corresponding uncertainty by taking a snapshot of the filter state when an interrogation event occurs, and propagating this quantity up to the reception instant.

Including delayed states as observables at a given instant of the filter update has been previously studied in the literature. To the best knowledge of the authors, it was first addressed in Brown and Hartman [1968], and is in line with recent developments regarding Out-Of-Sequence Measurements (OOSM), see Zhang et al. [2005] and references therein. Augmenting the state vector is also considered a standard procedure. In this work it is shown the relevance of including the interrogation state information and uncertainty in this type of observations, given that it is not a standard procedure in the design of underwater positioning and navigation systems.

The RTT measurements are fed into the filter by removing solely the known response delay

$$z_{r_i} = t_{i_{rtt}} - \bar{t}_D \tag{14}$$

The RTT measurements (14) are then considered to be approximately described by

$$z_{r_i} = \bar{t}_p + \bar{t}_{r_i} + \eta_i \tag{15}$$

where η_i represents the measurement noise for the ith receiver that corresponds to the quantization error at the receiver as in subsection 4.1, but includes quantization errors inherent to the detection process performed at the transponder.

Since the position of the transponder in the Earth coordinate frame is assumed to be known, the travel time from the pinger on the vehicle to the transponder can be computed given the position and attitude of the vehicle at the interrogation instant. The position of the pinger on the Earth coordinate frame is given by

$${}^{E}\bar{\mathbf{p}}_p = \bar{\mathbf{p}} + \bar{\mathcal{R}}\, {}^{B}\bar{\mathbf{p}}_p \tag{16}$$

and thus the travel time from the pinger to the transponder is given by

$$\bar{t}_p = \| \, {}^{E}\bar{\mathbf{p}}_t - {}^{E}\bar{\mathbf{p}}_p \| / v_p = \| \, {}^{E}\bar{\mathbf{p}}_t - \bar{\mathbf{p}} - \bar{\mathcal{R}}\, {}^{B}\bar{\mathbf{p}}_p \| / v_p \tag{17}$$

where ${}^{E}\bar{\mathbf{p}}_p$ is the position of the pinger in the Earth coordinate frame, and ${}^{B}\bar{\mathbf{p}}_p$ is the position of the pinger in Body coordinate frame. All quantities in (17) refer to the interrogation instant.

The transponder-receiver travel time $\bar{t}_{r_i}$ is given by (8). Similarly, using the approximation for the attitude error (2) and the position error definition (3) in (17) yields for the pinger-transponder travel time

$$\begin{aligned} \bar{t}_p \approx \| \, & {}^{E}\bar{\mathbf{p}}_t - \mathbf{p}_{k_i} + \delta \mathbf{p}_{k_i} \\ & - \mathcal{R}_{k_i} \, {}^{B}\bar{\mathbf{p}}_p - \left[\mathcal{R}_{k_i} \, {}^{B}\bar{\mathbf{p}}_p \times\right] \delta \boldsymbol{\lambda}_{k_i} \| / v_p \end{aligned} \tag{18}$$

where the subscript k_i indexes the interrogation instant.

To allow for the integration of the travel time lag, the filter state space is augmented when an interrogation event occurs by copying the original state x_k to the second part of the new augmented state, becoming $\tilde{x}_{k_i} = [x_{k_i} \; x_{k_i}]^T$.

The objective is to store and propagate the interrogation state x_{k_i} up to the reception instant t_{k_r}, by writing the filter equations as a function of both the reception and interrogation states. In this framework, the augmented state transition matrix becomes

$$\tilde{\phi}_k = \begin{bmatrix} \phi_k & 0 \\ 0 & I \end{bmatrix} \tag{19}$$

where the augmented identity matrix propagates the interrogation state in time until the reply from the transponder is available.

Upon reception of the reply from the transponder the state is updated using

$$\hat{\tilde{x}}_{k_r} = \hat{\tilde{x}}_{k_r}^- + \tilde{K}\left(z_{k_r} - h\left(x_{k_r}^-\right) - j\left(x_{k_i}\right)\right) \tag{20}$$

where $\tilde{K}$ is the augmented EKF gain, z_{k_r} is the set of RTT measurements (after the response delay is removed), $h\left(\hat{x}_{k_r}\right)$ is the set of nonlinear transponder-receivers travel time observation equations evaluated at the prior state estimate of the reception instant $x_r = [I \; 0]\, \tilde{x}$ using (8), and $j\left(x_{k_i}\right)$ is the nonlinear pinger-transponder travel time observation equation (the same for the entire set of receivers) evaluated at the updated state estimate of the interrogation instant $x_i = [0 \; I]\, \tilde{x}$ using (18).

The new observation Jacobian matrix at the instant of reception is given by

$$\tilde{H}_{k_r} = [H_{k_r} \; J_{k_i}] \tag{21}$$

where H_{k_r} is the previously formulated observation Jacobian matrix evaluated at the prior reception instant state, and J_{k_i} is the Jacobian matrix of the pinger-transponder travel time observation equation $j\left(x_{k_i}\right)$.

The state estimation error covariance matrix for the augmented state is created when the interrogation is executed and is given by

$$\tilde{P}_{k_i} = \begin{bmatrix} P_{k_i} & P_{k_i} \\ P_{k_i} & P_{k_i} \end{bmatrix} \tag{22}$$

where P_{k_i} is the original state estimation error covariance matrix at the interrogation instant k_i.

The augmented EKF is computed using the same set of equations (11-12) but rewritten using the augmented matrices $\tilde{\phi}_k$, $\tilde{P}_k$, $\tilde{H}_k$, and $\tilde{Q}_k$ that results from padding the original state noise covariance matrix Q_k with fictitious zero mean white noise in order to increase the filter robustness to linearization errors and numerical problems (Gelb [1974]). Upon reception, the augmented state is deleted and the filter can proceed with the original state variables until a new interrogation is executed.

It is interesting to remark that the system is only required to be augmented with the states used in the observation

(18). In this case, the state estimation error covariance matrix is only augmented with the lines/columns of P_k accordingly to the augmented states.

5. SIMULATION RESULTS

The overall navigation system performance was assessed in simulation to show the relevance of including the interrogation instant uncertainty in the EKF. The USBL array is composed of four hydrophones (acoustic receivers) and one projector (acoustic receiver and emitter), installed on the nose of the vehicle according to the configuration depicted in Fig. 3 and detailed in Fig. 4. The maximum distance between the receivers is 20 cm, which are mounted on a non coplanar configuration. The pinger on the vehicle interrogates the transponder every 1.5 seconds, leaving enough time after the reception of the reply for disturbance phenomena like multi-path to fadeout on the channel.

The Time-Of-Arrival (TOA) of the acoustic waves arriving at the receivers are considered to be disturbed by zero mean Additive White Gaussian Noise (AWGN) with a variance of $(50\mu s)^2$ prior to the quantization procedure (note that this AWGN is the same for all receivers and that the differential disturbance is induced by the quantization). The TOA at the transponder is also considered to be disturbed by AWGN with the same variance, and the quantization was performed with a sampling frequency of 400 kHz.

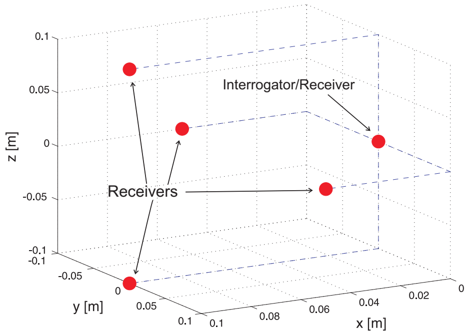

Fig. 4. Receivers installation geometry

The INS provides measurements of the position, velocity and attitude with a frequency of 50 Hz. The white Gaussian noise and bias characteristics of the sensors are presented in Table 1. A magnetometer is also used in the proposed solution, as presented in Morgado et al. [2006], yielding attitude estimation improvements. The noise and bias characteristics used in the simulations are inspired on the Crossbow CXL10TG3 triaxial accelerometer, the Crossbow CXM113 triaxial magnetometer, and on the Silicon Sensing Systems CRS03 triaxial rate gyro.

Table 1. Sensor characteristics

Sensor	Bias	Standard Deviation - σ
Rate gyro	5 °/s	0.05 °/s
Accelerometer	12 mg	0.6 mg
Magnetometer	(Calibrated)	60 μG

As illustrated in Fig. 5, the vehicle follows a path composed by an initial movement directly toward the transponder placed at an initial distance of 1000 m from the vehicle, and followed by a curve to a heading of 20 degrees while descending to a depth of 30 m at 100 s of the mission time. During this initial approach the vehicle describes a series of small helicoidal shaped curves to excite any non-observable modes of the system, which become otherwise unobservable during straight line paths, as discussed in Morgado et al. [2006]. An outage of USBL observation is forced when the vehicle turns to a heading of 90 degrees and starts descending to 50 m at 160 s, causing the USBL array to be out of Line-of-Sight (LOS) to the transponder (depicted in red in the figure, and has a duration of 30 s). Finally, the vehicle turns north, and regains USBL measurements while stabilizing at a depth around 50 m.

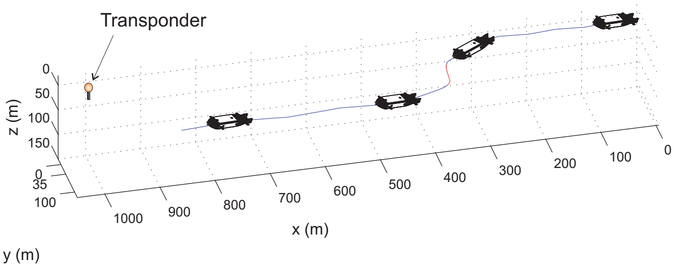

Fig. 5. Vehicle trajectory

The performance of the overall navigation system, using the Tightly-Coupled EKF with RTT division by 2 (referred to as TCEKFD2) and the Interrogation State Augmentation Tightly-Coupled EKF (referred to as ISATCEKF) was assessed in a Monte Carlo simulation composed of 20 runs. The Root-Mean-Square Estimation Error (RMSEE) in position is plotted in Fig. 6, where it is also depicted in a transparent magenta band the USBL observations outage period, and the filters corresponding 2-sigma estimated bounds. The USBL position fixes obtained by a method that resorts to the planar-wave approximation of the acoustic wave, presented by the authors in Morgado et al. [2007], are also marked on the plots (after correctly represented on Earth coordinate frame), evidencing the poorer positioning performance of standalone USBL systems (with very low update rates) compared to that of the high update rate position estimates of aided USBL/INS navigation systems.

As expected, during the initial path toward the transponder, the position estimate of the TCEKFD2 filter for coordinate x clearly attains higher RMSEE due to the relative motion between the vehicle and the transponder. In fact, the RMSEE for this situation evidences the expected position error inherent to this strategy: about half the traveled distance by the vehicle between the interrogation and reply from the transponder. For instance, between the interrogation at 51 s and the reply received at 52.2 s, the vehicle displacement is of about 3.1 m. Looking at the zoom around 50 s depicted on Fig. 6, the RMSEE holds at about 1.58 m, which corresponds to half of the traveled distance during the RTT of the acoustic signals. Obviously, this position bias decreases as the vehicle approaches the transponder and the lag between interrogation and reply gets smaller.

Other trajectories were considered and studied, however the selected trajectory routes the improvement of the proposed technique to a single channel, coordinate x where the major displacement is done, and emphasizes the performance enhancement. The improvement is not evident for coordinates y and z as the distance traveled in

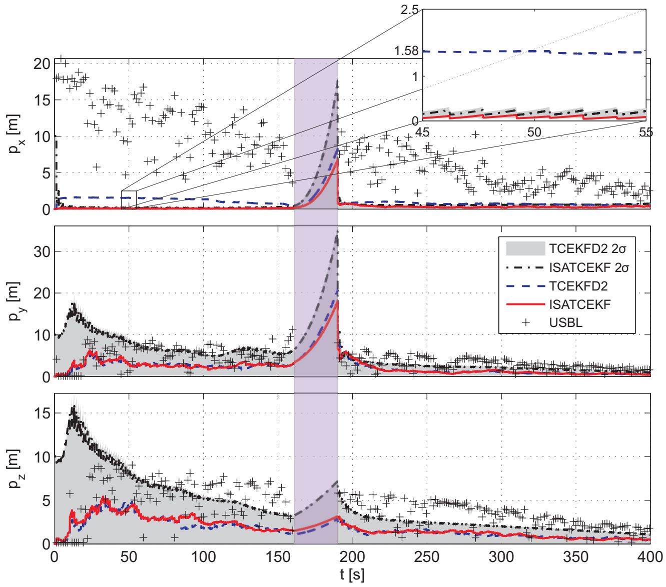

Fig. 6. Position RMSEE from 20 Monte Carlo runs

this directions is small compared to the traveled distance in x and the distance to the transponder.

Focusing on the period of USBL blockage, it can be clearly seen that the filters estimates drift from the nominal trajectory. When the USBL observations are again available, the filters estimates successfully converge to the true position of the vehicle. Additional analysis from the Monte Carlo simulation on the predicted error covariance of the filters and the outputs RMSEE also revealed the consistency of the ISATCEKF filter throughout the entire path including the USBL blockage situation, whereas the TCEKFD2 filter became inconsistent essentially during the initial path toward the transponder.

6. CONCLUSIONS

This paper presented two Tightly-Coupled techniques of fusing information from an USBL and an INS, yielding enhanced inertial quantities estimates, when compared to standalone USBL positioning devices. The method that comprehended the inclusion of the interrogation state estimates and respective uncertainty, was presented to enhance the performance and robustness of the overall navigation system by exploiting the information of the entire RTT of the acoustic signals, opposed to the commonly used method of halving of the RTT to obtain the travel times between the transponders and the vehicle.

The expected improvement and relevance of this fusion technique to the overall navigation system was confirmed based on Monte Carlo simulation experiments. The results presented in this paper compared the performance of two filtering techniques based on the assumption that the underwater environment is homogeneous and the underwater sound velocity is constant and known. The existence of different underwater layers and sound velocity profiles leading to ranging errors, may degrade the overall performance of both systems. Future work will focus on studying the effects of sound velocity variations, refraction of sound waves on the underwater layer boundaries and on the implementation and field validation of the proposed algorithms in real mission scenarios.

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