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Real-time underwater positioning and navigation of an AUV in deep waters

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Real-time underwater positioning and navigation of an AUV in deep waters

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Abstract— ***Due to the absence of GPS, navigation of autonomous vehicles underwater requires the integration of various measurements to provide the best location estimate. Usually in littoral waters, adequate navigational accuracy may be obtained by integrating odometry measurements provided by a Doppler Velocity Log (DVL) into an Inertial Navigation System (Aided INS). However, due to the bulk attenuation of seawater at the acoustic centre frequency at which DVLs typically operate, odometry estimates become increasingly unreliable when the vehicle flies more than 200 m above the bottom (depending on the DVL central frequency). Such a case occurs during experiments in deep waters. This work addresses a theoretical and experimental study on the feasibility of navigating the AUVs using a multi-input Extended Kalman Filter (EKF) integrating proprioceptive measurements (i.e., INS data and speed-over-water observations from DVL) with a set of exteroceptive sensor data, when available. The filter was integrated on-board the CMRE Ocean Explorer Class Version C (OEX-C) AUVs, and tested at sea for the first time in deep water during the NATO exercise Dynamic Mongoose'17 off the South coast of Iceland (June-July 2017).***

Keywords— ***Autonomous Underwater Vehicles; Deep Water navigation; Extended Kalman Filter; Data Fusion***

I. Introduction

Navigation of Autonomous Underwater Vehicles (AUVs) remains a challenging task, requiring a trade-off between performance, cost and operational time.
Solutions to solve the AUV navigation are based on the integration of expensive intertial sensors commonly in combination with Fiber Optic Gyros (FOG) to compute a measurement of the vehicle attitude, with pressure sensors to measure the depth and bottom DVL to estimate the vehicle speed over the seafloor [1]. To reduce the drift in the localisation error, different approaches can be used. In Long-BaseLine (LBL) solutions some beacons supporting the AUV navigation are moored around the operation area, while in Ultra-Short BaseLine (USBL) the distance/bearing is measured with respect to a support vessel with known position [1].

Today these solutions are being complemented by the use of services which novel networks of vehicles can provide. Teams of robotic nodes can indeed exchange information and use cooperative localisation approaches to support the navigation of the team members [1], [2]. In these kinds of approaches, each vehicle improves its self-localisation using range/bearing measurements obtained periodically from the other network nodes via acoustic communication. These approaches offer the opportunity to allow the navigation of a team of vehicles without the need of a deployed support infrastructure as the moored beacons in traditional LBL.

This work is a step towards these novel navigation systems. It addresses the enhancement of the navigation performance of an AUV through the development of a Deep Water Navigation Filter (DWNF) that is able to work in those scenarios where traditional navigation sensors show their limits: e.g., deep waters where DVL bottom lock cannot be achieved, or areas where the use of static and dedicated beacons is incompatible with the mission requirements. To achieve the goal of a deep water navigation suitable for long term missions without returning to the surface, a set of exteroceptive sensors has to be considered. In most scenarios, the AUVs represent the movable assets of a wider infrastructure (i.e. autonomous sensor network) or are immersed within a structured environment (e.g. supporting vessel with an acoustic positioning system such as an ultra-short baseline - USBL) that can be used to enhance the localisation and navigation capability of the vehicles. The proposed approach is based on the investigation of using additional/alternative localisation devices (e.g., acoustic positioning system such as HiPAP™, USBL, network-produced range measurements, etc.) to be fused within a real-time navigation filter capable of combining localisation data together with the vehicle odometry.

The approach proposed, that extends the work in [3] and [4], is well represented by the following three keywords:

- Heterogeneous – it refers to the source of measurements. It is important to differentiate the available sensors in order to maximize the probability of providing the navigation system with observations even in the case one or more of the involved sensor data are missing, e.g., because of adverse environmental conditions.
- Complementary – it refers to the adopted sensors. This property is fundamental to ensure the availability of observations beside the limits of one or more involved technologies. In this case (e.g. beyond the maximum functioning range of a particular device), the availability of complementary sensors is the chosen solution to maintain a sufficient accuracy level of the filter output.
- Opportunistic – it refers to the navigation filter itself. The involved sensors, characterized by a heterogeneous and complementary nature according to the two previous points, are mostly based on underwater acoustic communication framework. As the reliability, update rate and quality of the information made available by the acoustic sensors strongly depend on the environmental conditions, operational constraints and geometry, the navigation filter has been developed to exploit all the measurements as soon as they are available (opportunistic behavior).

The system considered exploits a network of mobile (either surface or underwater, either manned or unmanned vehicles) and static (buoys) nodes with respect to which the considered AUV can measure relative direction (through USBL) and relative distance (round trip time – RTT – by means of underwater modems). Moreover a HiPAP™ is hull-mounted on the support ship to measure the position of the network nodes. All the information is shared among the different nodes to support the navigation (*cooperative filter*).

The framework chosen for sensor fusion is an Extended Kalman Filter (EKF). In order to handle the delays between the instant of measurement and the availability of the data and to exploit also measurements that are older than the ones already available due to possible communication delays, the developed DWNF maintains a memory of the past estimations, inputs and measurements with associated timestamps. As soon as a new observation is available, it is applied in the right instant of the past, then all the following inputs and measurements in the database are re-applied in order to update the following estimates.

Section 2 describes the details of the algorithms implemented; the selection of results presented in Section 3 comes from extensive tests conducted at sea in real-time during a NATO operational exercise, Dynamic Mongoose'17, off the South coast of Iceland (June-July 2017). Conclusions are drawn in Section 4.

II. The EKF filter

Fusion of measurements derived from acoustic sensor data available within the whole hybrid network of manned and unmanned nodes is the basis for estimating the AUV position along time and is carried out through the design of an appropriate EKF. This is based on a kinematic two dimensional (horizontal plane) model (depth is reliably measured by means of the onboard pressure sensors) that is driven by signals of the speed and the course over water (model inputs $\left[s_{ow,k}\ \theta_{ow,k}\right]^T$ with k the discrete time index) provided by the DVL with no bottom-lock. The filter state, further than horizontal position components along the North and the East directions $\left[x_k\ y_k\right]^T$, includes also the components of the sea current velocity along same directions $\left[u_k\ v_k\right]^T$. We consider the sea current velocity components constant (uniform current model, according to [5]), except for a white Gaussian noise representing the model uncertainties along the two directions ($\nu_u \sim N(0,Q_u)$ and $\nu_v \sim N(0,Q_v)$). This approach allows to estimate the sea current simultaneously with the navigation state. This is a remarkable advantage as the system input, intensity and direction of the speed over water, is directly dependent by the sea current. Through the possibility of exploiting its estimation within the prediction step of the navigation filter, a more reliable output of the filter is expected even in the case of correction lack for a certain period (because of the nature of the acoustic channel, this may happen despite the use of heterogeneous sources of information and complementary sensors).

The process model equations used for the prediction step of the filter are:

$$\begin{aligned} x_{k+1} &= x_k + \Delta t\left(\tilde{s}_{ow,k}\cos\tilde{\theta}_{ow,k} + u_k\right) \\ y_{k+1} &= y_k + \Delta t\left(\tilde{s}_{ow,k}\sin\tilde{\theta}_{ow,k} + v_k\right) \\ u_{k+1} &= u_k + \Delta t \nu_u \\ v_{k+1} &= v_k + \Delta t \nu_v \end{aligned} \quad (1)$$

The input is a noisy signal as it is obtained as DVL measurements. It is thus modelled as the sum of the actual value of the measured quantity and a zero-mean Gaussian noise.

$$\begin{aligned} \tilde{s}_{ow,k} &= s_{ow,k} + \nu_s \\ \tilde{\theta}_{ow,k} &= \theta_{ow,k} + \nu_\theta \end{aligned} \quad (2)$$

with $\nu_s \sim N(0, Q_s)$ and $\nu_\theta \sim N(0, Q_\theta)$.

As it concerns the observation model for the available acoustic measurements, the adopted expressions are reported in the following:

- **HiPAP™** – the positioning system is integrated on the support vessel. Relative position measurements can be converted in absolute position with respect to the local reference NED frame through the integration with the navigation system (position and heading) of the vessel. NED measurements of the AUVs absolute position are communicated by exploiting the acoustic network and they are used for the estimation correction through the model:

$$\boldsymbol{z}_{HiPAP} = \begin{bmatrix} x_k \\ y_k \end{bmatrix} + \boldsymbol{\eta}_{HiPAP} \quad (3)$$

  where an additive zero-mean Gaussian noise $\boldsymbol{\eta}_{HiPAP}$ is considered. It is worth to underline that, in case of surface navigation (e.g. after deployment before mission starting) with GPS access, after conversion from Latitude and Longitude coordinates to the local NED frame, an analogous model can be used.

- **USBL** – the acoustic modems used for the exchange of messages within the acoustic network have USBL capabilities. On the reception of a message, the device is thus able to derive a measurement of the direction of arrival (DOA). This is an observation of the navigation state that is used for the update step of the filter according to the model:

$$z_{USBL} = \operatorname{atan2}\left(\tilde{y}_{i,k} - y_k, \tilde{x}_{i,k} - x_{i,k}\right) + \eta_{USBL} \quad (4)$$

  that is a function of the position $\left[x_{i,k}\ y_{i,k}\right]^T$ of the remote asset that sent the message. atan2 is the four-quadrant inverse tangent function and η_{USBL} models the measurement noise. The position of the remote asset is modelled as a random variable defined as the sum of the actual position and an additive zero-mean additive noise. It is estimated in parallel on-board through dedicated filters that exploit information, shared through the network, about the position of the various assets.

- **Network-produced range** – by means of a navigational layer implemented on top of the network, according to the details described in [6], timestamps enclosed in the exchanged messages are used to compute the Round Trip Time (RTT) and, thus, through a local indirect measurement of the speed of sound, the distance with respect to the remote asset. This approach does not require the addition of dedicated specific hardware. The range, this way computed, is compensated for the depth difference between the two involved nodes (the AUV and the remote asset) and is used as a navigation state observation according to the measurement model:

$$z_{rng} = \sqrt{\left(\tilde{x}_{i,k} - x_k\right)^2 + \left(\tilde{y}_{i,k} - y_k\right)^2} + \eta_{rng} \quad (5)$$

  where an additive zero-mean Gaussian measurement noise η_{rng} has been assumed. Considerations about the position of the remote asset reported for USBL DOA measurements apply also in the case of network-produced ranges.

It is worth to highlight that for the use of the above described acoustic measurements, information shared in the network is necessary. According to the means access policy (Time Division Multiple Access – TDMA is used in this case) and to the environmental conditions, the required information may be available on-board with a non-negligible delay. In order to deal with this unavoidable phenomenon, the developed DWNF maintains a memory of the past estimations, inputs and measurements with associated timestamps. A database is associated per each of the three variable types. The database is designed to maintain the various entries ordered by associated timestamp. When a new measurement with an associated timestamp older than the one of the last computed estimate is available, it is added in the right position and the history collected in the database is used. In particular, all the estimations more recent than the measurement timestamp are deleted. The most recent remaining estimation is used to apply immediately all the subsequent measurements and inputs through standard prediction and update steps of the EKF paradigm. This way, the last estimation resulting from the various iterations correctly takes into account the new information [7]. The same solution is adopted in the case of availability of delayed inputs.

The DWNF is designed to deal with the typical issues related to the acoustic measurements. In particular, a policy of outlier detection and rejection is implemented. The approach is based on the computation of the Mahalanobis distance associated to each measurement. The resulting value is compared with thresholds derived for each sensor on the basis of an extensive analysis of historical data collected during recent years for the involved sensors during NATO STO CMRE experimental activities. Measurements that are associated to a Mahalanobis distance greater than the relative threshold are identified as outliers and their use for the update step is rejected [8].

Further than the EKF that runs on the AUV with the objective of estimating its own navigation state, other EKF instances, customized on the basis of available sensors, are allocated either on the AUV itself or on the other network mobile nodes in order to filter or smooth local measurements. A key role is played by the filters that are implemented on board the support vessel.

Here, a filter per each asset that houses on-board a HiPAP™ transponder is implemented. The main goal is to estimate the position of these assets, but other useful benefits can be obtained. Since these filters are not executed on the vehicle of which the navigation state is estimated, they do not have direct access to the variables that may be considered the process inputs. The model described at the beginning of this section is, thus, not suitable for the purpose. The model of an autonomous (no input) system is used for the prediction step of the filter. The purely kinematic model includes, among the state components, the position $[x_k\ y_k]^T$ and the velocity $[\dot{x}_k\ \dot{y}_k]^T$ of the asset in the North-East reference frame:

$$
\begin{aligned}
x_{k+1} &= x_k + \Delta t\, \dot{x}_k \\
y_{k+1} &= y_k + \Delta t\, \dot{y}_k \\
\dot{x}_{k+1} &= \dot{x}_k + \Delta t\, \nu_{\dot{x}} \\
\dot{y}_{k+1} &= \dot{y}_k + \Delta t\, \nu_{\dot{y}}
\end{aligned}
\tag{6}
$$

The process noise $[\nu_{\dot{x}}\ \nu_{\dot{y}}]^T$ $[v_{\dot{x}}\ v_{\dot{y}}]^T$, affecting only the velocity components, models the uncertainty on the asset dynamics. Through the HiPAP™ observations, the state estimation is corrected. The measurement model for these filters is the same used for the filters on the AUVs.

Thanks to frequent HiPAP™ measurements (the sensor, although based on acoustics, does not interfere with the communication as it works on different frequencies) a reliable estimation of the AUV motion is calculated on the support vessel for mission monitoring purposes. The resulting estimation is a smoothing of the HiPAP™ measurements (smoother EKF). This approach offers an immediate added value. The outlier detection and rejection algorithm based on Mahalanobis distance is applied also for these filters. This allows to identify potential outliers before injecting them in the network implying the double benefit of avoiding misleading measurements to arrive at the AUVs and not to occupy network bandwidth with bad information.

A filter of the same kind is used on-board the support ship to estimate the position of the USBL modem mounted on a towed depressor. The ship communicates with the network thanks to this device that is towed at a distance of about hundred meters. An accurate estimation of USBL position is of fundamental importance for the DWNF to work properly as the measurement models depend on it. In order to minimize the potential error due to wrong assumptions on the ship USBL position, a HiPAP™ transponder is mounted attached to the depressor itself. The ship USBL position that is shared on the network to support the navigation of the AUVs is the one estimated this way.

III. Selection of Experimental Results

The approach was tested at sea in real-time during a NATO operational exercise, the Dynamic Mongoose'17 (DMON17) experimentation, conducted off the South coast of Iceland (26 June - 6 July 2017). The objective of CMRE's Cooperative ASW programme participating to the DMON17 ASW exercise was to introduce new capabilities into a NATO ASW system and demonstrate them into operationally relevant northern environments characterized by deep water and bad weather conditions. For what concerns deep water navigation, the objective was to explore the feasibility of navigating CMRE AUVs using the DWNF proposed in Section 2 and integrating:

- AUV GPS position when available (on surface);
- USBL direction-of-arrival (i.e., bearing) measurements of other nodes equipped with an acoustic modem;
- Round-trip-time (RTT) measurements provided by the underwater acoustic modems linking the nodes of the manned-unmanned ASW network together;
- AUV position from HiPAP™ data coming from the mother ship, when available;
- Speed over water and course over water measurements from the DVL.

The DWNS was fully integrated in the control loop of the two CMRE OEX-C vehicles and was running in their backseat during all the different missions conducted in deep water configuration mode along the whole experimentation (up to about 11 h continuously). During its functioning the computed estimations were communicated to the front-seat that could take advantage of them to propagate the navigation state estimation based on its internal filter. The first positive result is that, during all the missions, the integration among all the involved components demonstrated to be reliable.

Furthermore, in general, various heterogeneous instances of the filter were simultaneously active, both on the OEX-C itself for the position estimation of the other assets and on-board the top side for an upstream rejection of the HiPAP™ outliers. No integration issues emerged during their functioning.

Among all the missions conducted along DMON'17 experimentation, the mission conducted by Groucho, one of the two OEX-C AUV's operating during the exercise, on July 5th, 2017, starting at 9:00 GMT and lasting 15795s (>4h) has been selected. It appears as the most significant as, for this mission, a lack of HiPAP™ was simulated in real-time, by imposing communication inhibition towards the AUV, for some parts of the path (see the HiPAP™ data received on-board the AUV with respect to those available on NRV

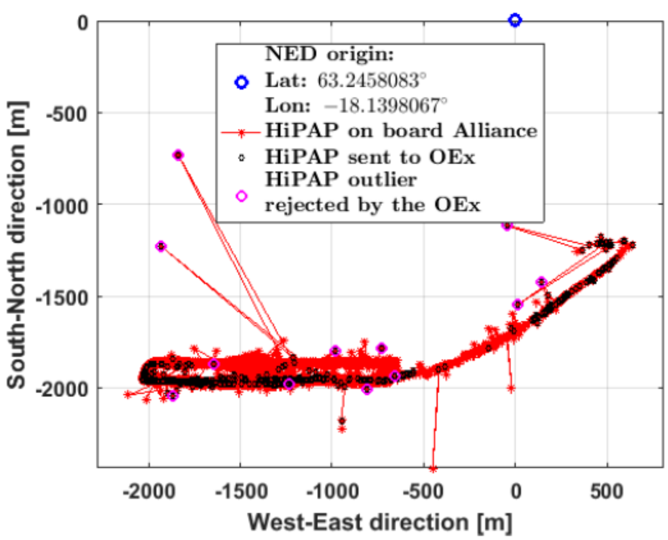
Alliance along the full mission, as represented on the North-East plane in Fig 1(a)). It is worth to notice that HiPAP™ is the most informative source of measurements, as they include absolute position.

These considerations make this mission a particularly suitable test case for the evaluation of the system performance under the lack of some measurements for long time periods (up to ~1 h).

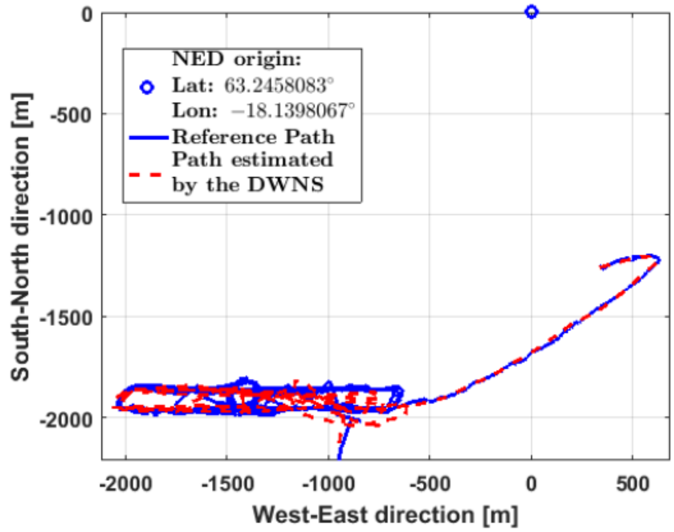
No Ground Truth (GT) is available for the considered missions. In order to evaluate the behaviour of the DWNS, as reference path (RP), the output of the smoother EKF which runs on Alliance and exploits, as observations, the OEX-C position measurements frequently available through HiPAP™, is considered.

As Fig. 1(b) shows the estimated positions compared to the RP, if one correlates the two plots realizes that position accuracy is degraded when HiPAP™ data are unavailable; however the filter, conceived and developed to be opportunistic with respect to the availability of observations, during these periods relied on the remaining available measurements. The vehicle is thus always provided with a reliable navigation state estimation (see the position error in Fig. 2(a)). It is interesting to notice in Fig. 2(b) the occurrence of data coming from USBL, RTT (and GPS) with respect to HiPAP™ and how they support the EKF to provide estimates when HiPAP™ is lacking. Given the sparsity of HiPAP™ data availability on board the AUV, the choice on an opportunistic method is clearly justified and results effective.

For the sake of completeness, Fig 3 shows the sea current intensity and direction estimated during the mission. A ground truth is not available to validate the estimation capabilities. Among the foreseen future steps, the comparison of the sea current estimation with simultaneous local measurements (e.g. through Acoustic Doppler Current Profiler – ADCP – from the ship) will be used for a rigorous validation.

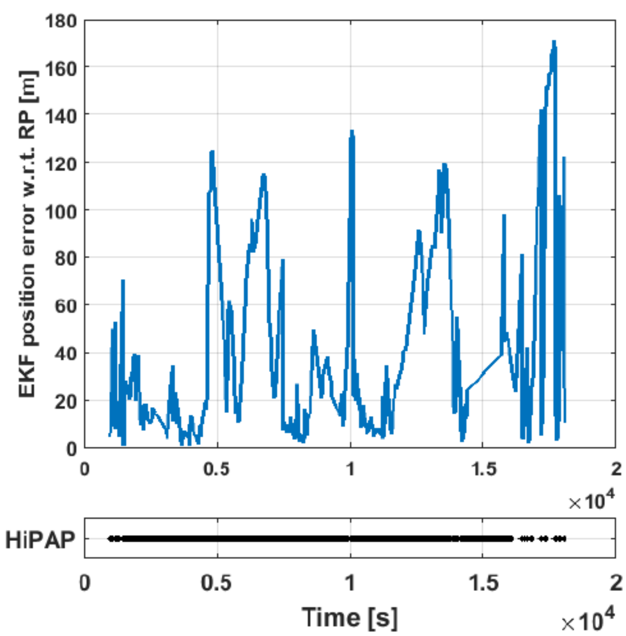


(a)

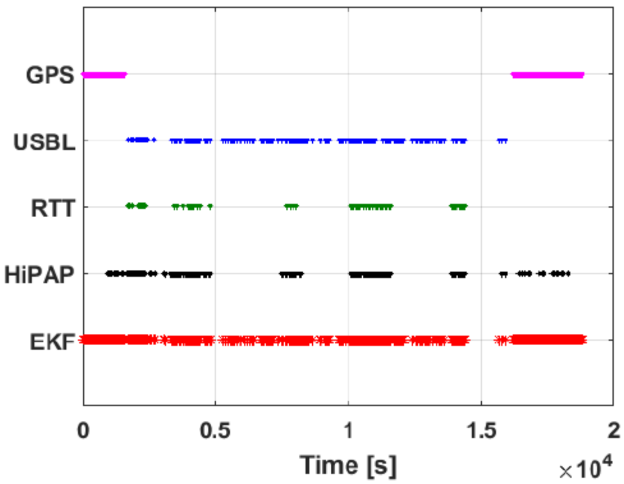


(b)

Fig. 1. (a) HiPAP™ measurements on Alliance and on Groucho OEX-C AUV, and identified outliers; (b) Estimated path compared with all the position measurements (GPS and HiPAP™) available, which contribute to the Reference Path (RP). The reference system selected is a Local Tangent Plane NED, the origin of which is indicated in the legendas.



(a)



(b)

Fig. 2. (a) EKF Position error along time. (b) Occurrences of measurements and estimations on Groucho AUV.

IV. Conclusions and future work

The main outcome of the results analysis is summarized in this conclusion section.

The DWNF was fully integrated in the control loop of the two CMRE OEX-C vehicles and it was running in their backseat during the duration of all the different missions conducted in deep water configuration mode between June 26 and July 6 (up to about 11 h continuously). During its functioning, the computed estimations were communicated to the front-seat that could take advantage of them to propagate the navigation state estimation based on its internal filter. The first positive result is that, during all the missions, the integration among all the involved components demonstrated to be reliable.

About the evaluation of the developed (cooperative and opportunistic) approach to the deep water navigation problem and of the performance of the DWNF, the results proposed in this paper are suitable to draw some first considerations.

First of all, the data analysis provided the evidence that the adopted approach has led to a filter capable of working with heterogeneous time-irregular and delayed measurements computing a navigation state estimation, in absence of DVL bottom-lock, suitable to avoid dedicated periodical re-surfacing during long lasting missions (demonstrated at sea up to about 11 h). The filter estimates also the direction and the speed of the sea current.

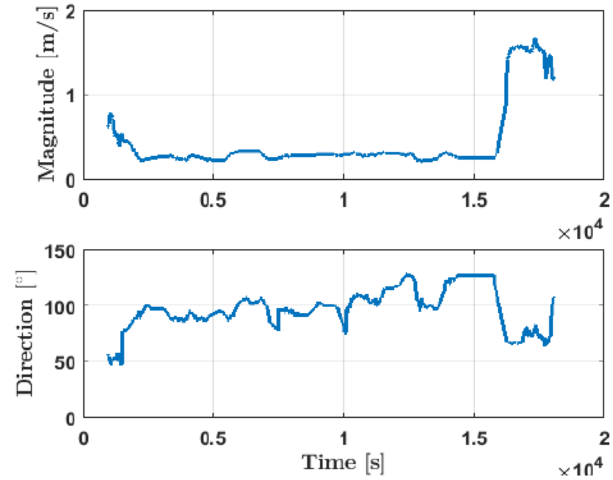


Fig. 3. Estimated sea current speed (in magnitude and direction). Unfortunately no ground-truth data were available along the sea trials.

In particular, each available measurement was integrated within the filter considering the particular instant when it took place. By means of maintaining a database, ordered on the basis of associated timestamps, including all the involved signals, it was possible to exploit the contribution of all the measurements. This avoids potential errors due the lack of synchronism of which underwater acoustic communication among a relatively complex network may suffer.

Further developments can be imagined in this phase oriented to make the filter output more reliable. Some possible refinements are proposed below.

- In many applications the actual situation is a hybrid between deep water and shallow water (or, in other words, DVL bottom lock may be intermittent). The filter may be developed in such a way to always accept water relative measurements (as it is currently) and bottom relative measurements when available. This extension is foreseen to increase the quality of the provided estimation of the navigation state and also of the sea current.
- Dynamic model: the model that is currently at the basis of the EKF prediction phase is purely kinematic. The implementation of a model that could exploit the knowledge of the vehicle dynamics is expected to increase the quality of the estimation, in particular, in the potential case of lack of measurements for long periods.
- The collection of experimental data about the sea current in the area where the vehicles operate is a fundamental step towards the validation of sea current estimation. This way, it will be possible to compare the estimated current with a reliable ground truth and, also, to finer tune the filter to obtain, in operations, a more accurate output.

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Title

Real-time underwater positioning and navigation of an AUV in deep waters

Abstract

Due to the absence of GPS, navigation of autonomous vehicles underwater requires the integration of various measurements to provide the best location estimate. Usually in littoral waters, adequate navigational accuracy may be obtained by integrating odometry measurements provided by a Doppler Velocity Log (DVL) into an Inertial Navigation System (Aided INS). However, due to the bulk attenuation of seawater at the acoustic centre frequency at which DVLs typically operate, odometry estimates become increasingly unreliable when the vehicle flies more than 200 m above the bottom (depending on the DVL central frequency). Such a case occurs during experiments in deep waters. This work addresses a theoretical and experimental study on the feasibility of navigating the AUVs using a multi-input Extended Kalman Filter (EKF), integrating proprioceptive measurements (i.e., INS data and speed-over-water observations from DVL) with a set of exteroceptive sensor data, when available. The filter was integrated on-board the CMRE Ocean Explorer Class Version C (OEX-C) AUVs, and tested at sea for the first time in deep water during the NATO exercise Dynamic Mongoose'17 off the South coast of Iceland (June-July 2017).

Keywords

Autonomous Underwater Vehicles; Deep Water navigation; Extended Kalman Filter; Data Fusion

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