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Joint Positioning and Navigation Aiding Systems for Multiple Underwater Robots ⋆

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Abstract: This paper proposes a new joint positioning and navigation aiding system for multiple underwater robots. In the scenario adopted, each submersed target carries a pinger that emits acoustic signals periodically, as determined by a low precision clock. The targets are tracked from the surface by a set of buoys equipped with acoustic hydrophones/projectors, GPS receivers, and electronic circuitry that measures the times of arrival of the acoustic signals emitted by the pinger. The buoys at surface, synchronized with the GPS timing, emit periodically distinctive signals that the underwater vehicles can use as aids to their onboard navigation systems. In the case where buoys drift away more than a pre-specified distance from their nominal positions, coded signals are emitted. The scheme proposed allows for the performance in the tracking and navigation systems to be independent from the number of targets present in the scenario of operation. Simulation results are presented to assess the performance of both the positioning tracker and a simplified onboard integrated navigation system.

Keywords: Navigation systems, Positioning systems, Marine systems, Extended Kalman filters.

1. INTRODUCTION

In the last decades, the marine community has witnessed fast paced developments in underwater technology. The use of sophisticated ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles) is now reality in a number of underwater operations that are extremely difficult to be carried out by humans or require tedious and time-consuming activities. The operation of these underwater robots poses considerable technical challenges, namely in what concerns the determination of their position and velocity. A number of technical solutions exist to the problem of computing the position of an underwater vehicle, the most common being Short Baseline Systems (SBL) and Ultra-Short Baseline Systems (USBL) Vickery (1998), or more recently the GPS Intelligent Buoy System - GIB Thomas (1998), Manual (1999). Currently, a number of techniques exist for reliable 3-D navigation systems of multiple underwater robots. Examples include the inverted USBL, as detailed in Morgado et al. (2007) and in references therein, terrain- or landmark-relative navigation systems Oliveira (2007), and Long Baseline Systems (LBL) Milne (1983).

This paper extends recent joint simultaneous positioning and aiding navigation systems proposed in Sousa et al. (2008), to a scenario where a number of underwater vehicles (autonomous and/or tele-operated) can interact during a mission. Inspired by the GIB approach, that system is composed by three segments: a) Surface Segment: consists of a synchronized net of hydrophones and pingers attached to surface buoys that are equipped with GPS receivers; b) Underwater Segment: the submerged targets that emit periodically distinctive signals that are received by each of the hydrophones installed on the surface buoys, which in turn transmit via radio the time of arrival of the signals (TOA) to a control station positioned on a support vessel or on land; and c) Control Segment: using Extended Kalman Filters (EKF), the control station computes the positions of the targets. Resorting to GPS timing, each buoy must send a signal that will be received by the targets and used as an external aiding signal by its onboard navigation system. In the case where a buoy drifts away from the pre-established position, a special signal is emitted encoding this quantity. The scheme proposed allows for a constant performance in the tracking and navigation systems, independent from the number of targets present in the scenario of operation. Moreover, note that to access this external navigation aiding data, no communication link is required, thus avoiding the requirement of operation of a difficult and at times very unreliable system.

The paper is organized as follows: Section II details a dynamical target model, specially suited for underwater vehicle survey missions, to be used by the Joint Positioning and Navigation aiding System for Multiple vehicles (JPNS-Multi). Section III discusses the adaptation of existing positioning systems for single vehicles, to a multiple vehicle scenario. Section IV describes in detail the Control Segment, namely the strategies to be implemented to tackle the problem at hand. Section V describes the navigation system that is at the core of the Underwater Segment,

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supported on the design of an EKF. In Section VI and VII the results of a set of simulated and real experiments, respectively, are summarized. Section VIII draws some conclusions on the proposed architecture and outlines future work.

2. TARGET MODEL

The main purpose of the JPNS-Multi is to provide support to missions with multiple underwater robots. The types of trajectories executed by the robot are instrumental in the development of a dynamical model that describes the targets movement. For instance, when considering typical bathymetric surveys, the following constraints can be assumed:

- the magnitude of the target velocity is constant;
- the mission is composed by a set of straight paths or curves of constant radius, i.e. trimming trajectories;
- the target trajectories are normally in the horizontal plane.

To match these assumptions, the Near Planar Constant-Turn Model (NCT) Li and Jilkov (2005) is adopted is this work. For other types of missions and robots, other constraints could be considered. Some basic notation is introduced next. Let

$$\mathbf{p}^t = \left[\, x^t \;\; y^t \;\; z^t \,\right]^\mathsf{T},$$

be the position of the target in an inertial reference frame

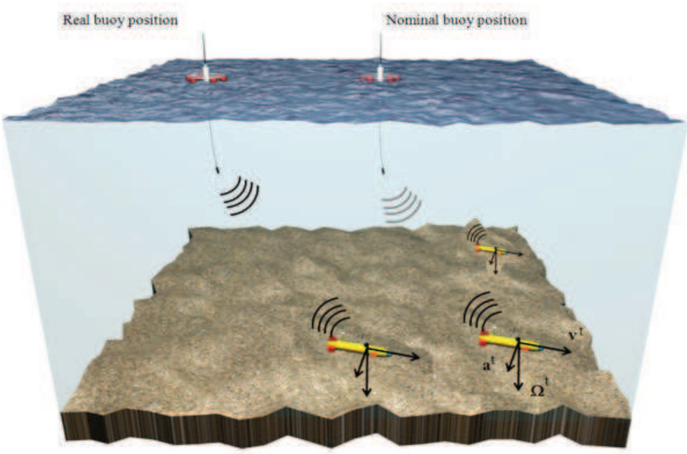

Fig. 1. AUVs interchaging data with bouys.

$I = O_{xyz}$, expressed as a column vector, verifying

$$\dot{\mathbf{p}}^t = \mathbf{v}^t,$$

where $\mathbf{v}^t$ is the target linear velocity, in the inertial frame. In the same reference frame, it verifies

$$\ddot{\mathbf{p}}^t = \dot{\mathbf{v}}^t = \mathbf{a}^t,$$

where $\mathbf{a}^t$ is the target acceleration and where the explicit time dependence was omitted. In this model it is assumed that the velocity vector is always aligned with longitudinal direction of the target, as depicted in Fig. 1. Given a continuous-time variable $u(t)$, $u(t_k)$ denotes its value at discrete instants of time $t_k = kT, \quad k \in \mathbb{N}_0$, and T denotes the sampling interval. Throughout this work, the time instant $T * (k) + \delta t$ will be denoted as $t_k + \delta t$, for the sake of compactness. It is now possible to define the continuous time kinematic model for the target as (see Li and Jilkov (2005) for a detailed derivation)

$$\dot{\mathbf{a}}^t = -\omega^2 \mathbf{v}^t + \mathbf{w}, \tag{1}$$

where ω is the turn rate (assumed to be known and constant) and $\mathbf{w}$ is Gaussian white noise. The dynamical model for the target state

$$\mathbf{x} = \left[\, x^t \;\; \dot{x}^t \;\; \ddot{x}^t \;\; y^t \;\; \dot{y}^t \;\; \ddot{y}^t \;\; z^t \;\; \dot{z}^t \;\; \ddot{z}^t \,\right]^\mathsf{T}, \tag{2}$$

is given by

$$\dot{\mathbf{x}}(t) = \mathbf{A}(\omega)\mathbf{x}(t) + \mathbf{B}\mathbf{w}(t),$$

where

$$\mathbf{A}(\omega) = \operatorname{diag}\left\{[\, \mathbf{C}(\omega) \;\; \mathbf{C}(\omega) \;\; \mathbf{C}(\omega) \,]\right\},$$
$$\mathbf{B} = \operatorname{diag}\left\{[\, \mathbf{D} \;\; \mathbf{D} \;\; \mathbf{D} \,]\right\},$$

$$\mathbf{C}(\omega) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\omega^2 & 0 \end{bmatrix}, \text{ and } \mathbf{D} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

the Gaussian white noise $\mathbf{w}(t) = [\, w_x(t) \;\; w_y(t) \;\; w_z(t) \,]^\mathsf{T}$ has power spectral density $\mathbf{S} = \operatorname{diag}\{[\, S_x \;\; S_y \;\; S_z \,]\}$. The corresponding discrete time model can be obtained using the method introduced in Farrell and Livstone (1993) to yield

$$\mathbf{x}(t_{k+1}) = f(\mathbf{x}(t_k), \mathbf{w}(t_k)) = H(\omega, T)\mathbf{x}(t_k) + \mathbf{w}(t_k), \tag{3}$$

where $\mathbf{H} = \operatorname{diag}[\mathbf{F}(\omega)\mathbf{F}(\omega)\mathbf{F}(\omega)]$, the disturbance covariance matrix is given by

$$\mathbf{Q}(\omega, T) = \operatorname{diag}\left\{[\, S_x\mathbf{J}(\omega, T) \;\; S_y\mathbf{J}(\omega, T) \;\; S_z\mathbf{J}(\omega, T) \,]\right\},$$

$$\mathbf{F}(\omega, T) = \begin{bmatrix} 1 & \dfrac{\sin\omega T}{\omega} & \dfrac{1-\cos\omega T}{\omega^2} \\ 0 & \cos\omega T & \dfrac{\sin\omega T}{\omega} \\ 0 & -\omega\sin\omega T & \cos\omega T \end{bmatrix}, \quad \text{and}$$

$$\mathbf{J}(\omega, T) = \begin{bmatrix} \dfrac{6\omega T - 8\sin\omega T + 2\sin 2\omega T}{4\omega^5} & \dfrac{2\sin^4 \omega T/2}{\omega^4} & \dfrac{-2\omega T + 4\sin\omega T - \sin 2\omega T}{4\omega^3} \\ \dfrac{2\sin^4 \omega T/2}{\omega^4} & \dfrac{2\omega T - \sin 2\omega T}{4\omega^3} & \dfrac{\sin^2 \omega T}{2\omega^2} \\ \dfrac{-2\omega T + 4\sin\omega T - \sin 2\omega T}{4\omega^3} & \dfrac{\sin^2 \omega T}{2\omega^2} & \dfrac{2\omega T + \sin 2\omega T}{4\omega} \end{bmatrix}.$$

This discrete time model will be used both in the Control Segment and in the Underwater Segment of the JPNS-Multi, as detailed in the next sections.

3. MULTIPLE TARGET SCENARIO

The recent joint positioning and navigation aiding system proposed in Sousa et al. (2008), denominated as JPNS, only addressed a scenario where only a single target was present. In a scenario where Z underwater targets are operating at the same time, Z replicas of the JPNSs would be required, in order to aid the navigation systems onboard all the targets. This fact would turn the multiple target mission scenarios expensive and not practical.

In order to generalize the problem previously stated, some solutions based on a typical positioning system, such as the JPNS, are now analyzed. Programming the buoys to send information independently to each target is the most obvious solution. This would be accomplished using for instance different frequencies on each buoys/target acoustic communication link. On this way it would be possible to implement a position and navigation aiding system to each target, with a number of buoys independent of Z. Then each buoy would transmit information Z times at each sample period (i.e. every T seconds the buoys would transmit one signal to each target). With this strategy the performance of the overall system would be similar to the basic positioning system . However, as the energy carried onboard is mostly used on the signals transmission, the energy consumption by the buoys would became a limiting factor for the mission duration. Moreover, each target added, would reduce the mission time by a factor of $1/Z$.

To overcome the energy consumption problem of this solution, an alternative approach could be implemented: to increase each target sample period to ZT seconds, thus the buoys would communicate to each target only each ZT seconds. As the emission period of the buoys would remain T seconds the batteries energy would be saved. This is a very simple solution but can reduce drastically the navigation systems performance onboard the underwater targets, as the navigation system would only receive new external aiding signals (probably to be fused as observations to a local EKF) at each ZT seconds.

The constrains found on both strategies described until this point are the consequence of adapting the basic positioning system for a single vehicle, to this new multiple targets scenario. Therefore a new approach must be advanced, aiming at achieving a performance and mission duration independents on the number of targets. Without loss of generality, it is assumed that the target and the buoys are synchronized in this new algorithm. The bias due to the low accuracy of the onboard clock can be easily estimated by each target, see Alcocer et al. (2006) for a reliable technique.

4. JPNS-MULTI: CONTROL SEGMENT

The positioning system central to this paper borrows from the key concepts introduced in the GIB system. In the setup adopted, the target carries a pinger that emits periodically a signal (every T seconds). This signal will be received by a net of N synchronized hydrophones attached to surface buoys equipped with GPS receivers. Each buoy records the Time of Arrivals (TOA) of the acoustic signals emitted by the pinger, together with its instantaneous GPS coordinates (given by the GPS receiver). The resulting data pack is then transmitted to the control station, where the target position is computed. The buoys emit distinct acoustic signals, all synchronized by the GPS time available at surface, used by the targets present on the mission scenario as external aiding signals.

At the beginning of each mission the initial positions of the buoys are set on the navigation systems of the targets $\hat{\mathbf{p}}_i^b = \mathbf{p}_i^b(0)$ (this value is stored in memory on the control station in $\breve{\mathbf{p}}_i^b$). The targets [1] assume that this is the correct localization of the buoys, until further information is received. If at time t_k one or more buoys have changed their position, due to wind, current, or other disturbances, more than δ_d from $\breve{\mathbf{p}}_i^b$, i.e.

$$\|\breve{\mathbf{p}}_i^b - \mathbf{p}_i^b(t_k)\|_2 \geq \delta_d,$$

the control station commands the buoys to send an acoustic signal coding the position correction. The frequency of this signal is proportional to the α_i angle. At this time the value recorded at $\breve{\mathbf{p}}_i^b$ was changed to $\mathbf{p}_i^b(t_k)$. An alternative strategy would be to communicate the movement direction of the buoys is to send two signals. The second signal would be delayed δ_T seconds from the first. This delay would be proportional to the angle α_i.

Once the signal of position correction is sent, the buoy will wait until all the targets reply with an acknowledge signal, meaning that the signal was correctly received. If any of the targets don't send the acknowledge signal, the buoy must resend the signal in order to ensure that it will be received. This way the performance of the system will increase.

When the target receives the correction signals, decodes the information relative to the direction of the buoy movement $\hat{\alpha}_i = \alpha_i + n_i^\alpha$ (n_i^α is stationary, zero-mean, Gaussian white noise with constant standard deviation σ_i^α). Next, neglecting the vertical movement of the buoys at surface, it computes the new buoy position $\hat{\mathbf{p}}_i^b$ using

$$\hat{x}_i^b = \hat{x}_i^b + \delta_d \cos(\hat{\alpha}_i),$$
$$\hat{y}_i^b = \hat{y}_i^b + \delta_d \sin(\hat{\alpha}_i),$$
$$\hat{z}_i^b = \hat{z}_i^b.$$

Since it was assumed the presence of errors when decoding α, the reference positions $\hat{\mathbf{p}}_i^b$ and $\breve{\mathbf{p}}_i^b$ are not equal.

Then the new reference values for the buoys position are set, and the operation continues (see Fig. 2). At each iteration the estimation error of the buoys position will increase. To capture this uncertainty, the value of σ_i should be increased accordingly.

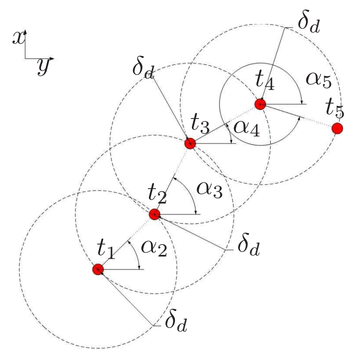

Fig. 2. Schematic representation of the system.

5. JPNS-MULTI: UNDERWATER SEGMENT

The network of N surface buoys available, equipped with GPS receivers, are used to send acoustic signals at the instants $s_i^b(t_k)$. When the target receives one of this signals (at the t_k instant) calculates the TOF between the buoy i and the target using

$$dp_i^a(t_k) = t_k - s_i^b(t_k). \quad (4)$$

To estimate the target position an EKF is proposed, thus a model to the measurements has to be introduced. When

[1] To simplify the notation no script will be used to identify which target is it referring to. Instead a generic description that can be equally interpreted for all the targets will be adopted.

a signal arrives, the target computes (4) and the result is fused in the target navigation system as

$$z_i^n(t_k) = \frac{\|\hat{\mathbf{p}}_i^b - \hat{\mathbf{p}}^t(t_k)\|_2}{v_{sound}} + n_i^n(t_k) \quad (5)$$

where $\hat{\mathbf{p}}_i^b = \left[\, \hat{x}_i^b \ \hat{y}_i^b \ \hat{z}_i^b \,\right]$ is the buoy i position estimate on the target, and $n_i^n(t_k)$ is a stationary, zero-mean, Gaussian white noise with standard deviation σ_i. The disturbances $n_i^p(t_k)$ and $n_j^p(t_k)$ are assumed to be independent for $i \neq j$.

Note that in (5) the target must know precisely the position of the buoys at the emission instants $\mathbf{p}_i^b(s_i^b(t_k)) \quad i = 1, \ldots, N$. As the use of an acoustic communication link would be a major limitation for this system, the communication between the surface and the underwater target is made resorting to a simple acoustic signal, as previously detailed. This signal will be sent every time that the buoys move a predefined amount δ_d, following a vector that makes an angle α_i with the y axis of the inertial reference frame I.

In the strategy adopted, all the N buoys send the navigation aiding signal simultaneously, however this signals can arrive at different time instants depending on the position of the target relatively to the buoys. In this way, the number of valid measurements o over an acoustic emission cycle varies from 0 to N depending on the target position and on the conditions of the acoustic channel $(0 \leq o \leq 4)$. This can be expressed as

$$\mathbf{z}'(t_k) = \mathcal{C}^o \left[\, \overline{z^n}_1(t^k) \ \cdots \ \overline{z^n}_N(t_k) \,\right]^{\mathsf{T}}.$$

The navigation system measurements vector is then

$$\mathbf{z}^n(t_k) = \left[\, \mathbf{z}'(t_k) \ z_z^n(t_k) \,\right]^{\mathsf{T}},$$

where $z_z^n(t_k) = z^a(t_k) + n_z^n(t_k)$ are the measurements of the depth available from a depth sensor ($n_z^n(t_k)$ is stationary, zero-mean, Gaussian white noise with constant standard deviation σ_z where $n_z^n(t_k)$ is independent of $n_i^n(t_k)$, $i = 1, \ldots, N$). It is also convenient to define

$$\mathbf{n}'(t_k) = \mathcal{C}^o \left[\, n_1^p(t_k) \ \cdots \ n_N^p(t_k) \,\right],$$

$$\mathbf{n}^n(t_k)) = \left[\, \mathbf{n}'(t_k) \ n_z^n(t_k) \,\right]^{\mathsf{T}},$$

$$\mathbf{R}' = \operatorname{diag}\{\mathcal{C}^n \left[\, \sigma_1 \ \cdots \ \sigma_N \,\right]\},$$

and

$$\mathbf{R}^n = \operatorname{diag}\left\{\left[\, \mathbf{R}' \ \sigma_z \,\right]\right\}.$$

The strategy adopted in the design of this navigation system resorts to a EKF. For the sake of its implementation, to be described later, it is now convenient to define the Jacobian matrices:

$$\hat{\mathbf{A}}^n(t_k) = \hat{\mathbf{A}}^n(\hat{\mathbf{x}}^n(t_k)) = \left.\frac{\partial f(\mathbf{x}, \mathbf{w})}{\partial \mathbf{x}}\right|_{\hat{\mathbf{x}}^n(t_k)},$$

$$\hat{\mathbf{L}}^n(t_k) = \hat{\mathbf{L}}^n(\hat{\mathbf{x}}^n(t_k)) = \left.\frac{\partial f(\mathbf{x}, \mathbf{w})}{\partial \mathbf{w}}\right|_{\hat{\mathbf{x}}^n(t_k)},$$

$$\hat{\mathbf{C}}^n(t_k) = \hat{\mathbf{C}}^n(\hat{\mathbf{x}}^n(t_k)) = \left.\frac{\partial \mathbf{z}^n}{\partial \mathbf{x}}\right|_{\hat{\mathbf{x}}^n(t_k)} \quad \text{and}$$

$$\hat{\mathbf{D}}^n(t_k) = \hat{\mathbf{D}}^n(\hat{\mathbf{x}}^p(t_k)) = \left.\frac{\partial \mathbf{z}^n}{\partial \mathbf{n}^n}\right|_{\hat{\mathbf{x}}^n(t_k)}.$$

where $\hat{\mathbf{x}}^n(t_k^t)$ is the estimated value of the state vector $\mathbf{x}(t_k^t)$. As the target model (3) is linear it follows that

$$\hat{\mathbf{A}}^n = \hat{\mathbf{A}}^n(t_k) = \mathbf{H}(\omega, T) \quad \text{e} \quad \hat{\mathbf{L}}^n = \hat{\mathbf{L}}^n(t_k) = \mathbf{I}_9),$$

Furthermore, by defining

$$\hat{\mathbf{C}}_z^n(t_k) = [\, 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1 \,] \quad \text{and}$$

$$\hat{\mathbf{C}}_i^n(t_k) = \begin{bmatrix} -\dfrac{\hat{x}_i^b - \hat{x}^n(t_k)}{\hat{\overline{d^n}}_i(t_k)} \\ 0 \\ 0 \\ -\dfrac{\hat{y}_i^b - \hat{y}^n(t_k)}{\hat{\overline{d^n}}_i(t_k))} \\ 0 \\ 0 \\ -\dfrac{\hat{z}_i^b - \hat{z}^n(t_k)}{\hat{\overline{d^n}}_i(t_k)} \\ 0 \\ 0 \end{bmatrix}^{\mathsf{T}}$$

with

$$\hat{\overline{d^n}}_i(t_k) = \|\hat{\mathbf{p}}_i^b - \hat{\mathbf{p}}^n(t_k)\|_2$$

and

$$\hat{\mathbf{D}}^n = \hat{\mathbf{D}}^n(t_k) = Id(o+1),$$

it follows that

$$\hat{\mathbf{C}}^n(t_k) = \left[\mathcal{C}^o \left[\, \hat{\mathbf{C}}_1^n(t_k) \ \cdots \ \hat{\mathbf{C}}_N^n(t_k) \,\right] \hat{\mathbf{C}}_z^n(t_k)\right]^{\mathsf{T}}.$$

An Extended Kalman Filter is proposed as a sub-optimal fusion strategy. The measurements available at each cycle, allow for the state and covariance update, otherwise a pure state and covariance prediction is performed.

At t_{k+1}, it is computed an *a priori* state estimate, using (6), and the *a priori* covariance matrix, using (7).

$$\hat{\mathbf{x}}_-^n(t_{k+1}) = \mathbf{H}(\omega, T)\hat{\mathbf{x}}^n(t_k). \quad (6)$$

$$\mathbf{P}_-^n(t_{k+1}) = \hat{\mathbf{A}}^n \mathbf{P}^n(t_{k+1}) \hat{\mathbf{A}}^{n\mathsf{T}} + \hat{\mathbf{L}}^n \mathbf{Q}^n \hat{\mathbf{L}}^{n\mathsf{T}}. \quad (7)$$

If any measurement is available the estimator performs an update to the *a priori* state and covariance matrix, producing the *a posteriori* state estimate $\hat{\mathbf{x}}_+^n(t_{k+1})$, as in (8), and *a posteriori* covariance matrix $\mathbf{P}_+^n(t_{k+1})$ (9). If no measurement is available the estimator will proceed to the next iteration.

$$\hat{\mathbf{x}}_+^n(t_{k+1}) = \hat{\mathbf{x}}_-^n(t_{k+1}) + \mathbf{K}^n(t_{k+1})[\mathbf{z}^n(t_{k+1}) - \hat{\mathbf{z}}^n(t_{k+1})] \quad (8)$$

$$\begin{aligned} \mathbf{P}_+^n(t_{k+1}) &= \mathbf{P}_-^n(t_{k+1}) - \mathbf{P}_-^n(t_{k+1})\hat{\mathbf{C}}^{n\mathsf{T}}(t_{k+1}) \\ &\quad \left[\hat{\mathbf{C}}^n(t_{k+1})\mathbf{P}_-^n(t_{k+1})\hat{\mathbf{C}}^{n\mathsf{T}}(t_{k+1}) + \hat{\mathbf{D}}^n \mathbf{R}^n \hat{\mathbf{D}}^{n\mathsf{T}}\right]^{-1} \\ &\quad \hat{\mathbf{C}}^n(t_{k+1})\mathbf{P}_-^n(t_{k+1}) \quad (9) \end{aligned}$$

$$\mathbf{K}^n(t_{k+1}) = \mathbf{P}_+^n(t_{k+1})\hat{\mathbf{C}}^{n\mathsf{T}}(t_{k+1}) \left[\hat{\mathbf{D}}^n \mathbf{R}^n \hat{\mathbf{D}}^{n\mathsf{T}}\right]^{-1}$$

The algorithm developed is modular, so when a measurement is available it will be evaluated at the next iteration of the cycle as if it was received at that instant. If the target is moving, this approximation can introduce some errors (see Fig. 3). In the worst case the error introduced is $T\mathbf{v}^a$ (sample period $\times$ target velocity). This way the sample period chosen is determinant for the overall system performance.

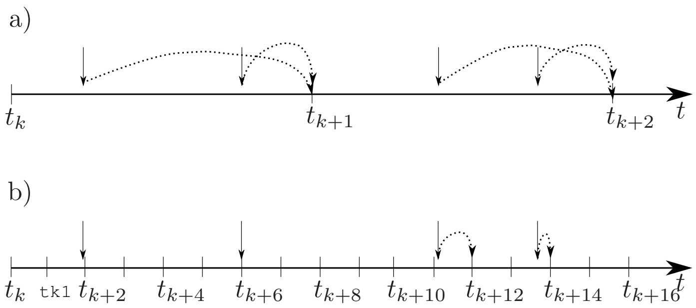

Fig. 3. Schematic representation of the moments of reception and evaluation of the navigation aiding signals. Figure a) has a greater T than that b). The dotted lines show the moment of evaluations of the received signals

6. RESULTS

This section describes the results obtained from a series of computer simulated experiments aimed at validating the proposed architecture and assessing its performance. In the simulations, the buoys were initially placed on a square configuration, with a side of 2 Km, and move at an average velocity of 100 m/h, in the West-East direction. Table 1 presents the initialization parameters for the simulation. The parameter β^n is the failure probability of a Bernoulli distribution, to describe the event of invalid of missing reception for each buoy, at each instant. This captures the well known fact that not all acoustic signals emitted are correctly received Alcocer et al. (2006). The actual and

Table 1. Simulation parameters

$T =$	$0.1\ s$
$\mathbf{x}_1(0)$	$\left[\, 50\ \ 0\ \ 0.025\ \ 10000\ \ -0.5\ \ 0\ \ 300\ \ 0\ \ 0 \,\right]^{\mathsf{T}}$
$\mathbf{x}_2(0)$	$\left[\, 150\ \ 1.77\ \ 0.001\ \ 150\ \ 1.77\ \ 0\ \ 400\ \ 0\ \ 0 \,\right]^{\mathsf{T}}$
$\mathbf{x}_3(0)$	$\left[\, -350\ \ 0\ \ 0.0133\ \ -50\ \ 2\ \ 0\ \ 100\ \ 0\ \ 0 \,\right]^{\mathsf{T}}$
$\hat{\mathbf{x}}_1^n(0)$	$\left[\, 55.7\ \ -0.0011\ \ 0.025\ \ 995.7\ \ -0.5017\ \ 0\ \ 298.8\ \ 0\ \ 0 \,\right]^{\mathsf{T}}$
$\hat{\mathbf{x}}_2^n(0)$	$\left[\, 138.2\ \ 1.8\ \ 0.001\ \ 151.8\ \ 1.8\ \ 0.0001\ \ 399.9\ \ 0\ \ 0 \,\right]^{\mathsf{T}}$
$\hat{\mathbf{x}}_3^n(0)$	$\left[\, -376.7\ \ 0.0007\ \ 0.0133\ \ -51\ \ 2\ \ 0.01\ \ 100.7\ \ 0\ \ 0 \,\right]^{\mathsf{T}}$
$P^n(0)$	$\mathrm{diag}\left\{ \left[\, 35^2\ \ 0.5^2\ \ 0.001^2\ \ 50^2\ \ 0.5^2\ \ 0.001^2\ \ 1^2\ \ 0\ \ 0 \,\right]^{\mathsf{T}} \right\}$
S	$\mathrm{diag}\left\{ \left[\, (0.001)^2\ \ (0.001)^2\ \ 0 \,\right] \right\}$
σ_i	$0.0033,\ i = 1, \ldots, 4$
σ_z	1
σ_i^α	$i = 1, \ldots, 4$
β^n	0.1
δ_d	$5\ m$

estimate target trajectories are depicted in Fig. 4 for the experiment described above. Figure 5 depicts the error between the actual and the estimated trajectories of all the targets. Note that these results are independent of the number of targets.

As the system performance is closely related with the buoys position estimates of the targets, Fig. 6 depicts this estimation error. The buoys position estimation error does not returns to zero when a navigation aiding signals is received because of the n_i^α noise. If the mission duration is longer or if the buoys travel faster this estimation error can reduce the system performance.

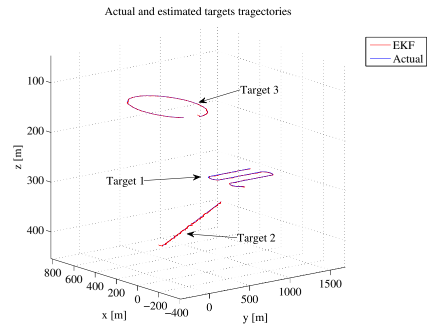

Fig. 4. Simulated and estimated trajectories.

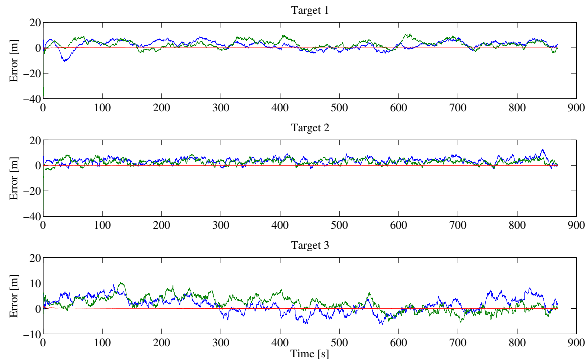

Fig. 5. Error between actual and the estimated trajectories. The error on the coordinates x, y and z are represented in blue, green and red, respectively.

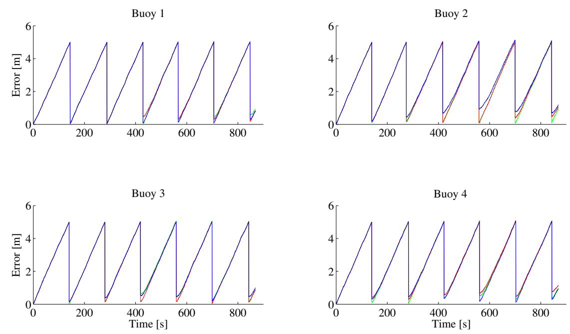

Fig. 6. Error between actual and the estimated buoys positions. The targets 1, 2 and 3 estimation errors are represented in blue, red and green, respectively.

7. EXPERIMENTAL RESULTS

In this section, experimental results obtained during sea tests in real operating conditions are presented. In Fig. 7, the experimental setup is depicted, namely the control station connected to a personal computer for display and logging tasks and a buoy drifting freely at sea, under the influence of the wind and sea currents disturbances. The results here reported do not correspond to the implementation of the overall JPNS-Multi, but to some of its main features, and aim to validate the fundamental ideas behind the proposed system. In the performed experiments, a pinger was submerged in a calibrated position, at a

Fig. 7. Experimental setup: left) PC connected to the control station; right) buoy drifting in the sea.

depth of $15\,m$, and a buoy was left drifting at the surface. Profiting from the GIB characteristics, the pinger and the buoy were synchronized. The control system was installed at surface, in a small support vessel. The main feature to be tested in these experiments was the determination the validity on the choice of the time instants in which the navigation aiding signals should be sent. These time instants correspond to an error distance of $\delta_d = 5\,m$ between the buoy actual position and its previous reference position. The pinger position (calibrated in the installation moment) and the buoy trajectory are depicted in Fig. 8. As can be seen, initially the buoy was left at a distance of approximately $100\,m$ from the pinger, and then the buoy drifted away from its initial position, which occurred due to the influence of currents and wind. Given this behavior experienced during the 15 minutes experiment, it is clear the importance on the proposed strategy for the buoy to aid the targets navigation systems. Figure 9 depicts the distance between the buoy position in each time instant and its previous reference position, thus the time instants in which the navigation aiding signals should be emitted become clear. It is possible to verify that the buoy average velocity is approximately $400\,m/h$, which is a value on the order of the one considered in the simulation process.

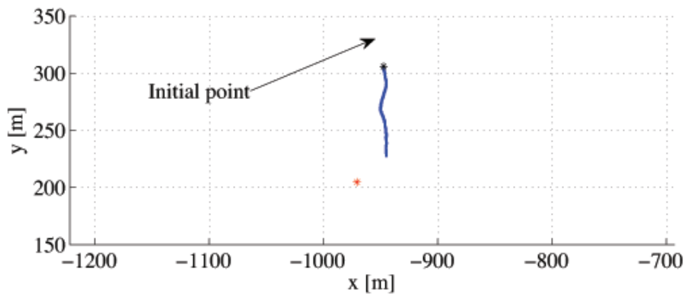

Fig. 8. Buoy trajectory (blue) and pinger position (*).

8. CONCLUSION

This paper described a new joint positioning and aiding navigation system that provides both positioning data and navigation aids simultaneously for several targets, composed by three segments: a) Surface Segment: consists of a synchronized net of hydrophones and pingers attached to surface buoys that are equipped with GPS receivers; b) Underwater Segment: the submerged targets that emit periodically signals that are received by each of the hydrophones at the buoys, which then transmit via radio the time of arrival of the signals to a control station positioned on a support vessel or on land; and

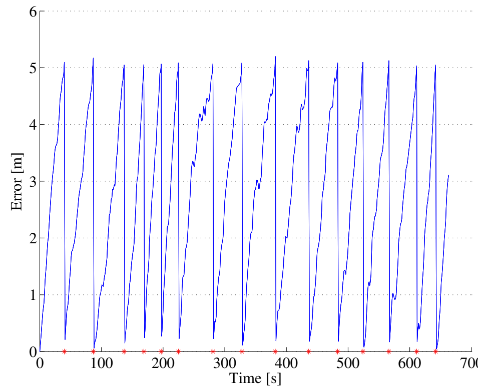

Fig. 9. Error between the buoy reference and real positions (blue), and instants in which the navigation aiding signals should be sent (in red).

c) Control Segment: using an Extended Kalman Filter (EKF), the control station computes the position of the targets. Resorting to a signal coding the displacement of the buoys, relative to their nominal positions, a system with performance independent of the number of targets is obtained. Simulation results for the JPNS-Multi have shown the viability of this approach as an improvement for the simultaneous operation of multiple underwater vehicles. These simulation results were complemented with some preliminary results from sea tests performed in real operating conditions. In the near future the overall proposed architecture will be implemented and tested at sea.

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