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Temporal combination of positioning modes for AUV navigation in perturbed environments

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Abstract

In this paper we present a positioning system for AUV's that relies on the possibility of using its acoustical subsystem in two distinct modes: a high accuracy active mode, which is energy consuming, and a degraded passive mode, which requires no emission from the vehicle. This enables efficient use of the available on-board energy, by providing reliable estimates of external forces acting upon the vehicle (sea currents), and allowing a minimum amount of active interrogation of the acoustic transponders. The paper presents the entire architecture of the positioning system and simulation results that demonstrate the importance of careful distribution, along the mission, of the active navigation mode.

1 Introduction

This paper describes the positioning system of a small low cost Autonomous Underwater Vehicle whose purpose is to realize 3D surveys, acquiring a map of the variation of oceanographic parameters (salinity, turbidity, ...) in a pre-specified volume of the ocean. The small dimensions and cost restrictions associated to the platform preclude the on-board installation of sophisticated inertial sensors, which are restricted to the basic minimum required for the low level control of the thruster and of the control surfaces. The high level guidance of the vehicle resorts, in this case, to position and attitude estimates derived from external sources in order to close the control loop. Since no GPS positioning is available inside the water column (electro-magnetic waves being strongly attenuated by the water), an external acoustic subsystem must be used for positioning purposes.

In the most basic configuration, this acoustic subsystem, formed by at least two acoustic emitters/receivers at known (calibrated) positions, allows the vehicle to obtain measurements of its position in a fixed frame via triangularization, by measuring the distance with respect to each reference. Since each measurement of distance requires an **active** interrogation from the vehicle, the rate at which successive distance measurements can be obtained is limited by the (slow) propagation speed of the sound in water, and by the available on-board energy.

Unmodelled external perturbations acting on the vehicle, such as ocean currents, lead to systematic deviations from the nominal vehicle trajectory, which require further energy consumption to correct them. Efficient estimation of these perturbation forces can thus result in important energy gains: (i) it enables pre-compensation of current induced deviations and (ii) it allows a lower rate of active reference interrogation to achieve the same error level. Currents result in a modification of the nominal (unperturbed) relation between the direction of the vehicle velocity vector and its attitude angles (which are measured on board). Their estimation, thus, requires a good identification of the true velocity vector of the vehicle. Since the lower bound on the rate of active interrogation does not enable good estimation of the vehicle instantaneous velocity, in our positioning system the acoustic references can work in another alternative (**passive**) mode, which allows the measurement of velocity (by measuring Doppler shifts, i.e., the vehicle's radial velocity of the vehicle with respect to each reference).

To be able to track perturbating currents and at the same time guarantee the positioning accuracy required to correctly execute the pre-specified mission, our positioning system temporally combines the utilization of both modes of the acoustic subsystem.

The paper is organized as follows: the next section describes the architecture of the positioning system, discussing the importance of acoustic mode management and current estimation, and presenting simulation of the closed loop controlled system for a number of different schemes of utilization of the passive and active modes. Section 3 presents an initial identification phase, that provides good initial estimates of the current vector and of the compass bias. Finally, section 4 presents the models on which the distinct filters used for positioning are based.

2 Architecture

In order to fully motivate the architecture of the positioning system, we briefly describe the platform. It is a miniaturized AUV with a torpedo shape, with the propulsion at the rear. The vehicle can be steered in the vertical and horizontal directions. It comprises four main sections, see figure 1. A section at the rear, the Vector Control Unit (VCU), implements the low-level control of the vehicle. It is a classical control module, allowing the tracking of reference values for depth, speed, and yaw. The control signals of this module are directly derived from a set of on-board "navigation sensors" : a depth (pressure) sensor, a compass, an inclinometer, and a counter of shaft turns per minute. The section at the center of the vehicle is occupied by a computer board on which run the mission management and all positioning and guidance software. This section sends updated references to the Vector Control Unit, and triggers and stops the other two sections of the system. The next section contains the mission dependent payload, with instrumentation adapted to measuring the oceanographic parameters of interest. Finally, at the head of the platform, there is an acoustic emitter/receiver and associated electronics.

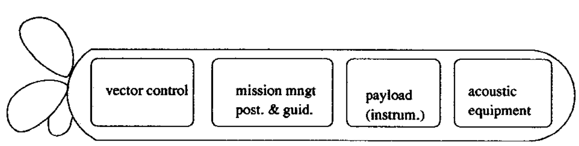

Figure 1: Organization of the platform's components.

As we briefly mentioned in the Introduction, the positioning system requires the execution of an initial phase, during which the vehicle executes a set of predetermined maneuvers to get an initial estimate of the current vector and an estimate of the bias of the compass (due to the magnetic field induced by other active components). Once these estimates are acquired, the vehicle then enters the actual mission, executing, in closed-loop, a pre-determined trajectory, defined by a sequence of way-points, using the estimated position/attitude/velocity and currents to generate corrected reference values for the VCU.

During mission execution, high-level control (which has now available good estimates of current and can pre-compensate yaw references for bias reading) is turned on. The principal role of the positioning system is to produce the best possible estimates of the vehicle position to the high-level control module. During this phase, the vehicle alternates between passive and active use of the acoustic references, interleaved with silent periods, during which the acoustic channel is used for other purposes (communication between the acoustic references and the vehicle). The control of the references' mode is made on line, the underlying goal being of keeping a good balance between energy consumption and positioning error.

Accurate knowledge of the vehicle position is of most importance near passage by the way-points that define the vehicle trajectory, where control is expected to impose a higher degree of maneuverability to the platform. Whenever the expected error near the way-points, predicted using analytical methods of error prediction [3] is greater than a pre-specified threshold, the acoustic references are forced to stay in active mode for a longer duration. Note that periodic use of the **passive** mode is necessary for tracking varying current fields.

As we discussed in the introduction, the objective of this platform is to produce 3D maps of a set of oceanographic parameters, which are measured by a reconfigurable user-dependent payload. In the mission definition, the user specifies a minimum rate of (vertical and horizontal) spatial sampling, and desired spatial accuracy of the retrieved samples. These specifications are also used on-line: whenever the estimated positioning error becomes too large, the positioning system forces **active** interrogation of the references. This on-line control manages the consumption of energy for positioning, resulting in a higher interrogation rate in the regions where the observability offered by the acoustic baseline is lower. The next figures illustrate the effect of acoustic mode management.

In the first figure the vehicle uses the acoustic references always in **passive** mode. Since, as it can be demonstrated theoretically [3], this mode leads to an error process which is a diffusion, the confidence of the vehicle on the estimated position degrades considerably, and leads to a distorted executed trajectory, as it is shown in figure 2. In this example, 20 seconds of acoustic (passive) emission are interleaved with 10 seconds of silence, during which positioning is made relying exclusively on on-board measures. The acoustic references are located near the surface, on the line $Y = -300m$, and at positions $X = 500m$ and $Z = -500m$. This figure is a 2D plot of the trajectory executed by the vehicle. It starts at position $(0, 0)$ and executes, in open loop, a set of pre-specified segments, and then proceeds to execute a trajectory that is defined by a set of 21 grid points distant, in the horizontal plane, of 500m, and alternating depths of 20 and 60 meters. The initial phase is discussed in the next section.

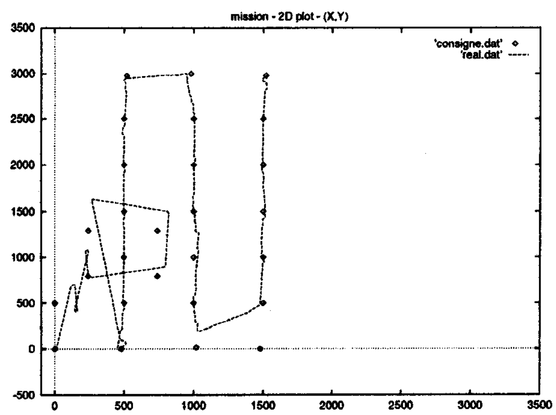

Figure 2: Trajectory using passive mode only.

The next figure shows the vehicle behavior obtained by ***interrogating the acoustic transponders*** (i.e., using **active** mode) ***only when approaching a way-point.*** That is, it replaces the next 20 seconds of passive emission by the references by an active interrogation/response behavior. We can see that this minimal amount of active use of the transponders is sufficient to allow control to correctly execute the pre-defined trajectory. Figures 4 and 5 show the trajectory segments during which passive and active modes are used, respectively, showing the high preponderance of the passive mode.

Finally, we plot in Figure 6 the simulated trajectory when the acoustic modes are used consecutively in a fixed alternating mode: 20 sec. active, 10 sec. silence, 20 sec. passive, 10 sec. silent. As Figure 6 shows, this unconstrained use of the acoustic references, requiring 2.5 times more energy, does not lead to a better vehicle behavior. Actually, this example shows that, more important than permanently keeping a high degree of positioning accuracy, what matters is to be able to produce reliable estimates at critical segments of the

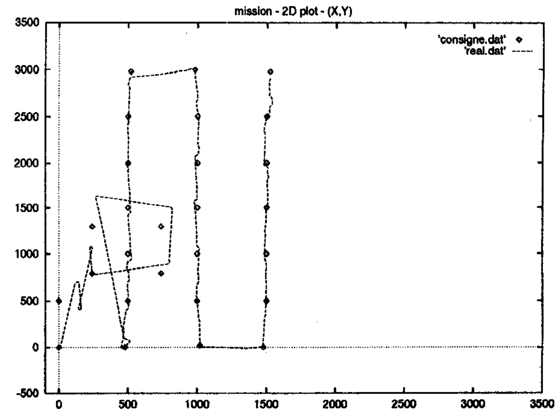

Figure 3: Trajectory forcing active mode approaching way-points.

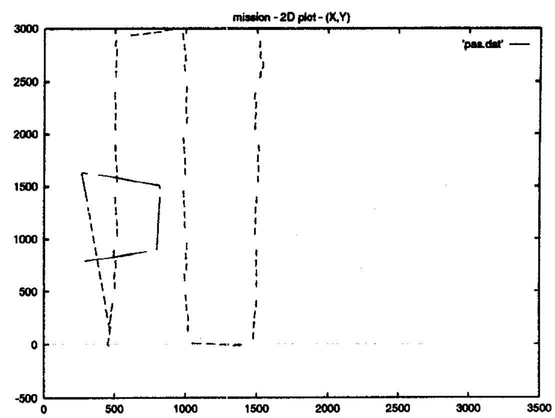

Figure 4: Segments of the trajectory in Fig. 3 executed in passive mode.

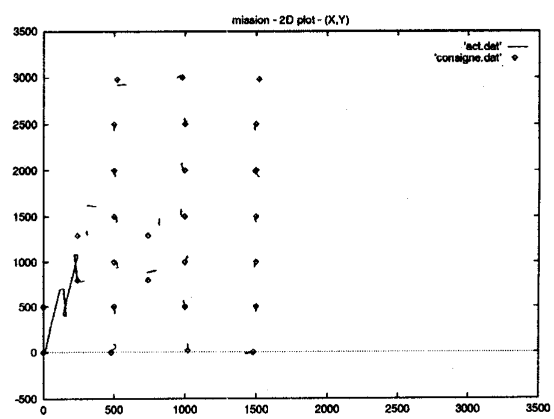

Figure 5: Segments of the trajectory in Fig. 3 executed in active mode.

trajectory.

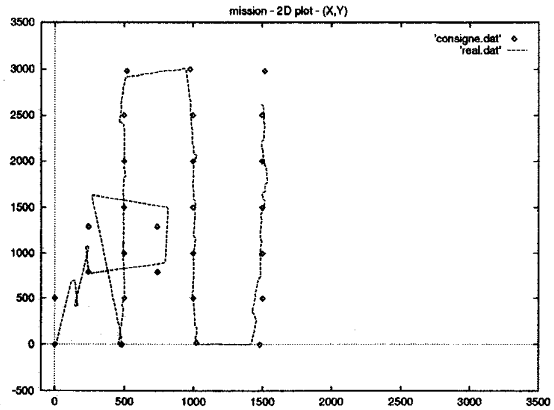

Figure 6: Trajectory under fixed alternating mode.

3 Identification Phase

As we stated in the introduction, we require the execution of a number of identification maneuvers priori to actual mission execution. This initial identification phase comprises two steps. The main objective of the first one is to estimate the compass bias, while in the second an estimate of the current field is acquired.

During the initial step the vehicle is launched, with the low-level control forcing it to execute $2N$ legs of constant *duration* T, at a constant depth z_0, constant speed V, and with reference values of yaw alternatively of $+\pi/2$ and $-\pi/2$, see figure 7. To obtain a trajectory as smooth as possible, high-level control is turned off during the entire identification phase. During all this time ($2NT$ seconds), the acoustic references work in **active** mode, providing estimates of the vehicle position (see section 4.1) independent of the compass offset and of the existence of currents.

For simplicity, assume that the initial position of the vehicle in the horizontal plane is $(0,0)$. Then, neglecting vertical currents, which are usually orders of magnitude smaller than their horizontal counterparts [4], its position in the horizontal plane x_n at the end of the n-th leg is:

$$x_n = x_{n-1} + (-1)^{(n+1)} TV \begin{bmatrix} \sin b \\ \cos b \end{bmatrix} + T \begin{bmatrix} c_x \\ c_y \end{bmatrix},$$

where b denotes the compass bias (the low-level control tries to set the *measured* attitude equal to the specified attitude), and (c_x, c_y) are the horizontal components of the current vector. Let Δ_n denote the differences

$$\Delta_n = x_n - x_{n-1} = (-1)^{(n+1)} TV \begin{bmatrix} \sin b \\ \cos b \end{bmatrix} + T \begin{bmatrix} c_x \\ c_y \end{bmatrix}$$

Then

$$\Delta_n + \Delta_{n+1} = 2T \begin{bmatrix} c_x \\ c_y \end{bmatrix}$$

$$\Delta_{n+1} - \Delta_n = -2TV \begin{bmatrix} \sin b \\ \cos b \end{bmatrix}$$

Or,

$$\begin{bmatrix} \sin b \\ \cos b \end{bmatrix} = \frac{\Delta_{n+1} - \Delta_n}{2TV} \qquad \begin{bmatrix} c_x \\ c_y \end{bmatrix} = \frac{\Delta_n + \Delta_{n+1}}{2T}$$

These equations form the basis for our compass bias estimation, providing also initial current estimates.

The equations above assume an instantaneous reaction of the vehicle to the change of reference values, which is not physically realizable, since the vehicle takes a non-zero interval to achieve a full π change on its attitude. For this reason, each normalized difference Δ_n/T in the equations below is replaced by

$$\frac{\Delta_n^\star}{T_n} = \frac{x_n(t_n^{exit}) - x_n(t_n^{entry})}{t_n^{exit} - t_n^{entry}}$$

where t_n^{entry} and t_n^{exit} are the time instants when a stabilized yaw is achieved in leg n, and before starting leg $n+1$, respectively.

Once these two initial estimates are obtained, a second identification step is entered, where the vehicle again executes, in open loop (only the low-level – reference following – control is active) a number of legs at constant speed and yaw. The goal of this second step is to acquire better estimates of the current vector. During this step, the positioning system works mainly in **passive** mode (the two acoustic references continuously emitting a synchronized signal), allowing a good estimation of the vehicle true velocity vector. Sporadic use of the active mode is however necessary to guarantee that the linearization of the passive Extended Kalman filter is done using a good position estimate.

Using the bias corrected compass reading, and the inclinometer and shaft speed measures, the current filter updates an estimate of the current field.

The next figures illustrate the identification step. Figure 7 shows the vehicle trajectory during the two steps. The vehicle starts by executing the two identifications steps, which consist of: *(i)* four legs of (nominally) 240m for bias/current estimation ($T = 60$ sec),

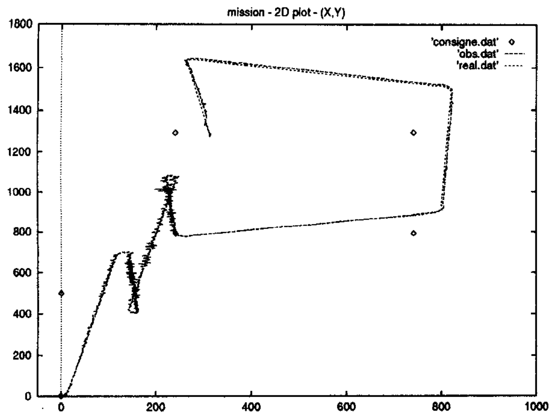

Figure 7: Identification step.

and a square of nominal side 500m ($T = 125sec.$) for current estimation. In the figure, we show both the true and estimated position.

The true bias of the compass in this simulation is 5^o, and the current is homogeneous and equal to $(.3, .9, .1)$. The first step produces estimates: $\hat{b} = 5.09628$ and $(\hat{c}_x, \hat{c}_y) = (0.31, 0.96)$, which are representative of the values obtained in the error conditions simulated.

Figure 8 illustrates the evolution of the current estimate during the second step. As it can be seen, the current estimates in the horizontal plane converge to their true values, while the small vertical current is underestimated. This is typical of the observed behavior, and is linked to the low observability of the vertical component of the velocity vector.

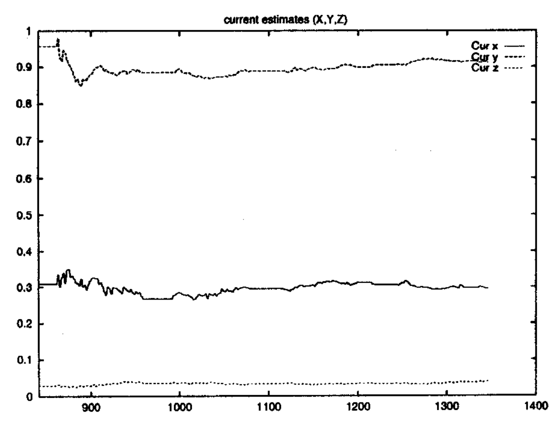

Figure 8: Evolution of current estimate.

4 Filters

In this section we briefly describe the architecture of the positioning system. The positioning system is illustrated in figure 9. It consists of five distinct filters:

- the *attitude* filter, which filters the on-board angular measurements provided by the compass and inclinometer;
- the *inertial* filter, which integrates the on-board measured speed (velocity w.r.t. the water), corrected by the estimated current, to produce new position and velocity estimates;
- the *active* filter, which yields position/velocity estimates on the basis of the measured distances to the acoustic references and the output of the depth sensor;
- the *passive* filter, which propagates the position/velocity estimates based on measured radial speeds and differential delay;
- the *current* filter, which uses on-board measured rotation speed and attitude angles, and the estimated instantaneous velocity of the vehicle, to update estimates of the current vector.

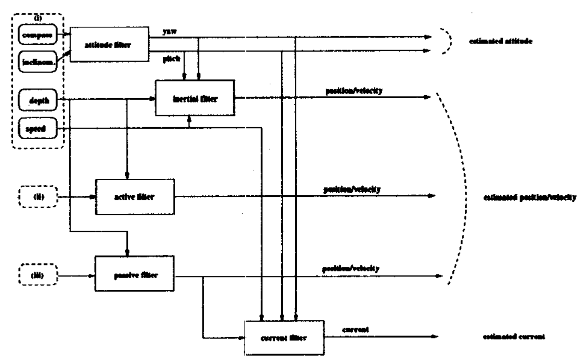

Figure 9: Architecture of the positioning module.

All these filters are Kalman (or Extended Kalman) filters, based on a locally constant acceleration model. Subsequent subsections detail the observation vector for each filter, and the error characterization for each one.

The main guideline that lead to this decoupled structure was a concern for the robustness of the estimates with respect to modeling issues. Due to budgetary constraints, no validated dynamic model of the vehicle is available. Moreover, no reliable characterization of the on-board speed and angular sensors has been provided by the platform constructor. In this conditions, it was important to provide position estimates which couldn't be contaminated by wrong models of the measured entities. For this reason, processing of acoustic data (both in active and passive modes) does not integrate the measured on-board velocity, nor the measured vehicle attitude. Moreover, with this configuration, correlation between the errors in current estimation – which strongly relies on the measured on-board speed and angular attitude – and the position errors is minimized.

4.1 Active filter

The active filter is used when the vehicle actively interrogates the two acoustic references, which, upon reception of the interrogating signal, answer in a prespecified frequency. The active filter processes the output of a triangularization block, that inverts the (x, y, z) position of the vehicle from the measurements of the round-trip travel time to the two acoustic references and the on-board depth measure. To keep the gain of this linear Kalman filter well tuned, in spite of the highly non-homogeneous characteristics of the triangularization error, on-line statistical modelization of the errors of this block is performed, computing the expected error level of the output of the triangularization block at each instant.

4.2 Passive filter

The passive filter is used when the acoustic references synchronously emit one signal. At the vehicle side, the two superimposed signals are received, and their relative time delay is measured, along with the Doppler shift suffered from each signal, [1].

Let $R_i(t)$ be the distance from the vehicle to reference i at time t. The passive filter is an Extended Kalman Filter whose input is: *(i)* the depth measure; *(i)* the difference $R_1(t)-R_2(t)$; *(iii)* the radial speed of the vehicle with respect to each reference, $\delta R_i(t)/\delta t$. The error characterization of these signals is passed to the positioning subsystem by the acoustic subsystem, which directly estimates them from the signal received by the vehicle's antenna.

4.3 Current filter

The current filter processes a "reconstructed" current signal s_n, derived from the on-board measured speed with respect to the water and the (passive) estimate of the complete velocity vector:

$$s_n = \hat{v}_n - V_n e(\hat{\theta}_n, \hat{\psi}_n)$$

where $\hat{v}_n$ is the estimated of the vehicle's velocity vector, V_n is the on-board measured velocity in the direction of movement, and $e(\hat{\theta}_n, \hat{\psi}_n)$ is the unit vector in the direction of the estimated vehicle's attitude. The gain of this filter is determined by the *a priori* knowledge about the spatial coherency of the current field – which determines the level of "state noise" – and by the predicted error level of the measurements s_n, based on the characterization of the signals and estimates that enter the expression above.

The statistical characterization of the dynamic noise of the state space of this filter takes into account the particular locations at which successive current estimates are updated, using existing a priori current knowledge about the current filter to properly control its bandwidth, [5].

Acknowledgments

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