

Simulation Study of an Integrated Guidance System for an Autonomous Underwater Vehicle

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ABSTRACT.

The paper discusses the design of a low cost and reliable guidance system for AUV's whose missions involve precise tracking of a prespecified trajectory. Advanced techniques concerning both the control and navigation subsystems are considered in order to achieve a true autonomous behavior of the vehicle. The control subsystem exhibits a high degree of robustness against vehicle parameters variations and rejects unknown sea currents disturbances. The navigation subsystem is based on Kalman-Bucy filtering techniques, trading between computational complexity and accuracy to achieve a control effort compatible with power consumption constraints. Integrated simulations are presented, showing the efficiency of the proposed guidance system.

1. Introduction

In many situations of practical interest, the specification of a typical mission for underwater exploration includes a precise definition of the trajectory to be tracked by an autonomous underwater vehicle (AUV). The design of advanced guidance systems for underwater vehicles, including sophisticated controllers and navigators, is of paramount importance if true autonomous behavior is to be achieved. The objectives of the guidance system are (i) to determine the position and attitude of the vehicle using a local navigation system and motion sensors, and (ii) to compute the commands to thrusters and elevators as to track the reference trajectory in the presence of varying sea currents and payload interchanging. Clearly, the accuracy of the navigation system is a crucial factor to reduce the control effort and therefore to improve autonomy by decreasing the power consumption. The general architecture of the guidance system is depicted in Fig. 1, where {A} and {B} denote the inertial reference frame and a body coordinate frame, respectively. The former is determined by an array of acoustic transponders placed on the sea bottom, and the latter is fixed with respect to the vehicle. Except for linear positioning, all the measurements are expressed in body coordinates {B}. The objective of the control system is summarized as follows: accept the external data concerning the estimates of linear and angular position and velocity and generate adequate commands to the thrusters and surfaces as to closely follow the reference trajectory. The control system is designed to exhibit a high degree of robustness against vehicle parameter variations and reject constant but unknown sea cur-

rent disturbances. The purpose of the navigation system is to provide accurate estimates of linear and angular position and velocity to the control system. Those estimates are based on measurements provided by a sensing system integrating a long baseline array system and linear accelerometers. Measurements of roll, pitch, yaw and their respective rotational speeds are also available. Kalman-Bucy filtering techniques are used to compensate for noise associated to angular and linear acceleration measurements, and to provide accurate estimates of linear position and velocity.

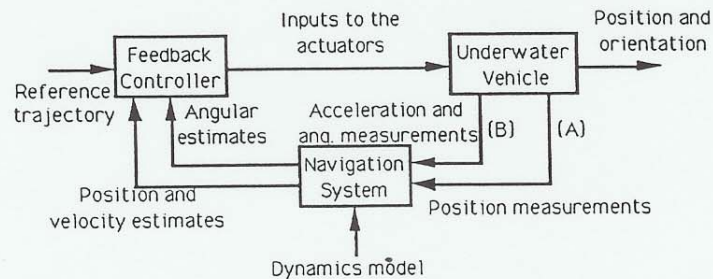


Fig. 1. Guidance System

This paper describes the control (section 2) and navigation (section 3) systems for an underwater vehicle for which a complete set of hydrodynamic derivatives is available [2]. Based on simulation studies, we discuss in section 4 the performance of the proposed guidance system, specially in what respects to the compromise between computational complexity, navigation accuracy and control effort.

2. Control System

For control purposes, the underwater vehicle under study is viewed as a rigid body that moves freely in the water under the action of forces and torques generated by electrical thrusters. The position and attitude of the vehicle are uniquely defined by the coordinates (x, y, z) of its center of mass expressed in $\{A\}$, and by the angles of roll, pitch, and yaw that describe the orientation of $\{B\}$ with respect to $\{A\}$. In the longitudinal plane, the vehicle moves along the depth coordinate z and "pitches" in response to two vertical thrusters. In the horizontal plane, the vehicle moves along the x, y coordinates and changes its yaw angle in response to two back thrusters and two side thrusters (for all purposes, these behave as one single horizontal thruster running across the center of mass the vehicle). The vehicle was designed to be naturally stabilized in roll.

The problem of designing feedback controllers to achieve precise control of an AUV in the presence of unpredictable sea currents and payload interchanging has attracted considerable interest in the literature. The plethora of methods at one's disposal includes one loop at a time classical frequency design, state-space design using energy like criteria (e.g. linear quadratic-LQ and linear quadratic gaussian-LQG), and variable structure control, to name but a few. In this project, we explored the use of recently developed control methods that bear the acronym of H-infinity design. This method rests on a firm mathematical basis, and addresses multivariable robust control design objectives that are akin to the by now classical single input-single output frequency design methods. The control design for the vehicle considered in this paper can be found in [2], to which the reader is referred for details.

3. Navigation System

3.1. ARCHITECTURE

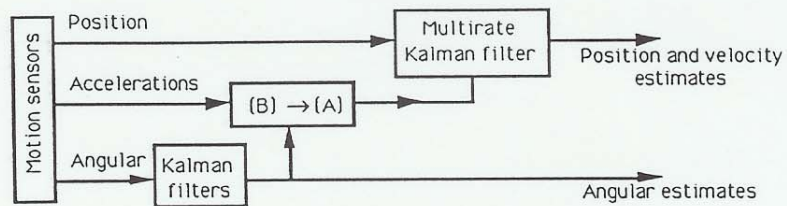


Fig. 2. Navigation System

The block diagram of the navigation system used in the simulations presented in this paper is outlined in Fig. 2. Estimation of the vehicle's position and linear velocity is performed based on measurements of its distance relative to three transponder units and the outputs of on-board accelerometers. Estimates of the vehicle's attitude (roll, pitch and yaw) are also generated, based on specific sensing systems that produce noisy measurements of these quantities, as well as their derivatives. In this paper, we concentrate on the generation of the first set of estimates. The angular estimates are produced by a set of three independent Kalman-Bucy filters, the yaw estimate being used to translate the on-board measurements of linear acceleration into global coordinates. The converted acceleration measurements, along with the observed position resulting from applying triangularization procedures directly to the round-trip travel time to each transponder unit, are then input to another Kalman-Bucy filter, yielding the desired estimates of the vehicle's position and linear velocity in the inertial frame.

The rate at which position information is available is variable, depending on the vehicle's position relative to the base-line array of transponder units. On the contrary, the accelerometers and the angular sensors can be sampled at a uniform rate, determined by the rate at which information must be made accessible to the control module. For the operational scenarios under consideration, it is anticipated that there will be need to generate positioning estimates at a rate faster than information is incoming from the transponder units. Modeling the (converted) acceleration measurements as a control input in the state model, the proposed filtering structure successfully circumvents this multi-rate character of the data. As it is well known, Kalman-Bucy filtering techniques are sensitive to modeling assumptions. To minimize these problems, we purposely avoid the integration of any complex models of the vehicle's dynamics describing the effect of the (known) actuator controls on the vehicle's trajectory. Instead, only very basic dynamic laws relating the measured quantities are used, and an effort has been put into finding adequate statistical descriptions of the errors associated to the available observations, to assure a convenient control of the filters' gains over all possible situations. These questions are briefly mentioned below, the interested reader being referred to [1].

3.2. MODELING ISSUES

The first filtering block shown in Fig. 2 yields estimates of the attitude of the vehicle (roll, pitch and yaw). These estimates are the outputs of standard Kalman-Bucy filters based on a linear first order model and a Gaussian noise assumption. Their gains are determined by

the (constant) sampling interval, and by the precision of the sensing devices, as furnished by the manufacturers. At this stage, no attempt has been made into incorporating more complex models of the sensors outputs. A slight reduction of computational load can be obtained, replacing these three filters by their stationary counterparts, or by approximations thereof, such like complementary filters or $\alpha - \beta - \gamma$ filters (see [3]). Notice that, of all angular estimates, only the yaw angle is relevant to the position and velocity estimation process, being used in the coordinate transformation block, that translates the measured linear accelerations into the global inertial frame. The second filtering block, yielding position and linear velocity estimates, is designed based on a first-order maneuvering model, the state vector being the (desired) vehicle's position and velocity, and the accelerations playing the role of (measured) external input. In this way, the constant rate acceleration information is used to propagate the state equation between the (non-uniform) sampling points of the vehicle's position. As stated before, a careful study of the error processes associated to the inputs of this filter has been conducted, leading to the following conclusions:

1 - Acceleration measurements (translated to global coordinates): assuming Gaussian errors in the linear on-board accelerations and on the yaw estimates, we conclude that this error process is non-homogeneous, having a non-zero mean (and thus requiring that bias compensation be done). Estimates of the associated mean and covariance are done in real time, using the current outputs of the navigation system.

2 - Position information (output of the triangularization block): assumption of uniformly distributed quantization errors in the time-delay measurements results in a non-homogeneous position error. Again, the current estimates of the vehicle's position and velocity are used to predict the statistical characterization of the data.

Analysis of the dependency of the error processes on the vehicle's position relative to the transponder units reveals that accurate error modeling is specially important at low altitudes, and on the limits of the region covered by the base-line array.

3.3. DISCUSSION

In this section we present several alternative designs to the Navigation System currently under study. These will be the subject of future reports.

No Acceleration Measurements - The architecture described here uses as basic sensing devices the array of transponders and accelerometers, thus enabling a controlled model approach. However, the high cost and low precision (in the order of typical vehicle's accelerations) of accelerometers currently available in the market led us to consider an alternative design that does not depend on the measurement of accelerations. Still keeping within a model-based approach, a variable dimension model is used, switching between a low dimension state space model for stationary (cruise) motion where acceleration is modeled as a random zero-mean process, and a higher dimension model for maneuvering intervals. This architecture retains the desired characteristics of transportability and modularity at reduced hardware costs, the price paid being increased software complexity and computational load.

Use of Doppler Measurements - A different design approach could incorporate Doppler sensors, as alternative to accelerometers. This hypothesis, although being theoretically interesting, puts some practical problems associated to the highly sophisticated output capabilities of available Doppler sonars, which involve costs unreasonable for small AUV projects. The development of AUV technology may in the near future lead to the availabil-

ity of simpler Doppler sonars, with functionality (and cost) adapted to the requirements of small maneuvering underwater vehicles.

Larger Base-Line Array - The present configuration uses only three transponder units. As we pointed out before, at low altitudes, and for some trajectories (e.g., when the vehicle is moving radially with respect to one of the transponder units), the observability offered by such an array is very low, leading to increased estimation errors. To alleviate this problem, future versions of the system will consider the utilization of more (at least four) transponders in the base-line array.

4. Integrated Simulation

The performance of the guidance system was evaluated in a simulation that includes the effects of a water current of -2 knot in the x -direction. The vehicle is required to follow the constant depth, U-shaped trajectory represented by the solid line in Fig. 3 (top-left), and to change the yaw attitude angle to keep its \underline{x} -body coordinate axis aligned with the tangent to the trajectory, see Fig. 3 (top-right, solid line). In both figures, the dotted line represents the actual trajectories obtained. With the scale adopted, the estimates provided by the navigation system appear to be coincident with the real trajectories. The real x and y linear velocities of the vehicle in the inertial reference frame, measured in meter/sec., are depicted in Fig. 3 (bottom-left). The estimated velocities match closely the actual ones. The control activity, as measured by the speeds of rotation of the propellers, is shown in Fig. 3 (bottom-right). The solid and dashed lines represent, respectively, the differential (yaw) and the common (x) modes associated with the back thrusters. The dotted line represents the common (z) mode of the vertical thrusters.

Notice in the first part of the maneuver the common mode activity of the back thrusters, which must counteract the current and propel the vehicle forward along the positive x -direction. During the last phase of the maneuver, the activity is reversed to slow down the vehicle in presence of the current which now tends to push it. The average value of the yaw control exhibits increased activity when the vehicle is turning. Notice also the positive residual activity in the vertical thrusters. Due to construction, the vehicle tends to move upwards whenever the back thrusters propel it forward. That activity is necessary to keep the z -coordinate under close control.

5. Conclusions

A guidance system for AUVs was designed and tested in a realistic simulation. Good performance was attained in the presence of sea currents, the control activity being kept at acceptable levels. Future work will consider the integration of diverse sensor configurations and controllers for faster maneuvering.

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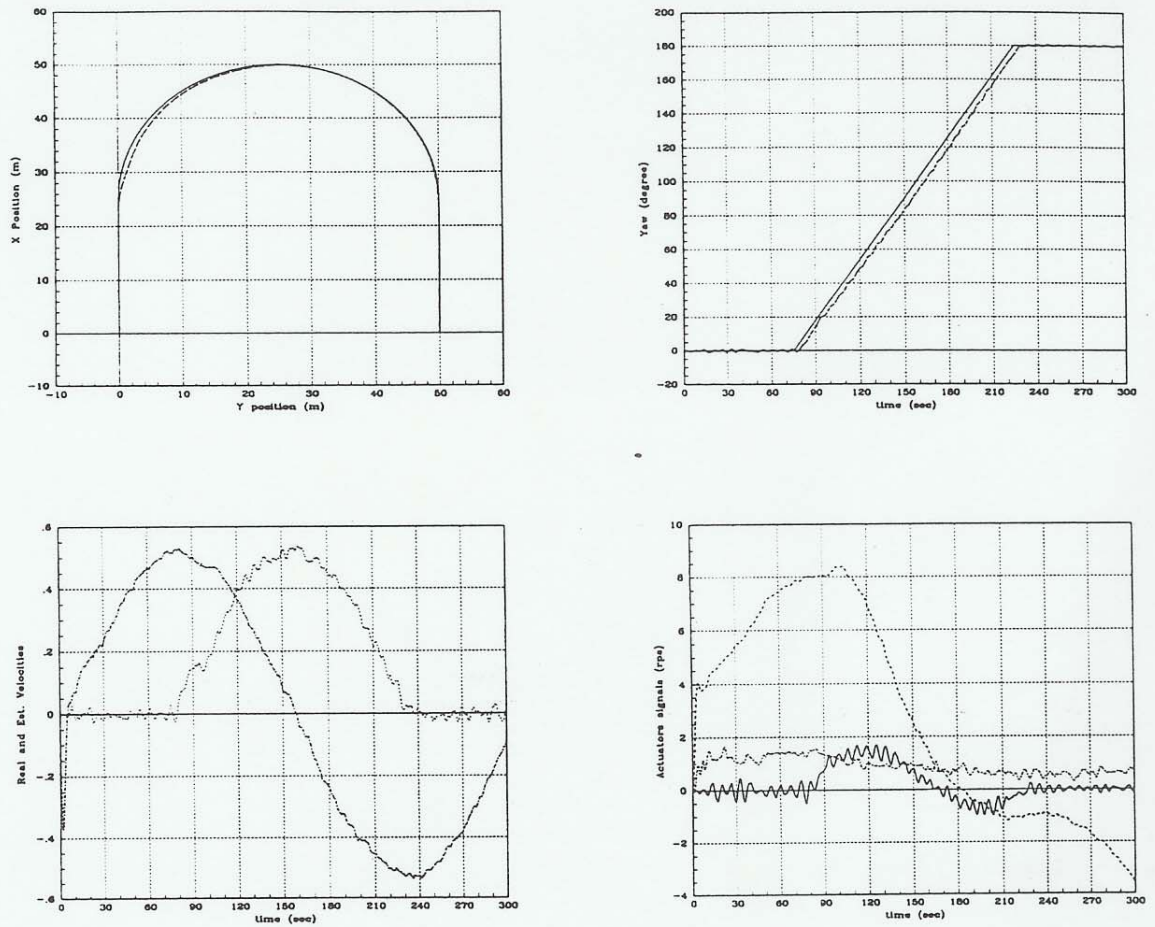


Fig. 3. Simulation results

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