Vehicle and Mission Control of the DELFIM Autonomous Surface Craft

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Abstract— **DELFIM is an autonomous surface craft developed at ISR/IST for automatic marine data acquisition and to serve as an acoustic relay between submerged craft and a support vessel. The paper describes the navigation, guidance, and control systems of the vehicle, together with the mission control system that allows end-users to seamlessly program and run scientific missions at sea. Practical results obtained during sea tests in the Atlantic, near Azores islands, are briefly summarized and discussed.**

I. Introduction

The paper describes the vehicle and mission control systems of DELFIM, an autonomous surface craft (ASC) developed for automatic marine data acquisition and to serve as an acoustic relay between submerged craft and a support vessel. The research and development effort that led to the development of the ASC was initiated in the scope of the European MAST-III Asimov project which set forth the goal of achieving coordinated operation of the INFANTE autonomous underwater vehicle and the DELFIM ASC, while ensuring fast data communications between the two vehicles, see [1]. This concept is instrumental in enabling the transmission of sonar and video images through a specially developed acoustic communications channel that is optimized to transmit in the vertical.

The DELFIM ASC can also be used as a stand-alone unit, capable of maneuvering autonomously and performing precise path following while carrying out automatic marine data acquisition and transmission to an operating center installed on board a support vessel or on shore. This is in line with the current trend to develop systems to lower the costs and improve the efficiency of operating oceanographic vessels at sea. See [2], [3], [4] and the references therein. Conventional oceanographic vessels require a large support crew, are costly to operate, and their availability is often restricted to short periods during the year. However, many oceanographic missions consist of routine operations that could in principle be performed by robotic vessels capable of automatically acquiring and transmitting data to one or more support units installed on shore. In the future, the use of multiple autonomous oceanographic vessels will allow researchers to carry out synoptic studies of the ocean on time and space scales appropriate to the phenomena under study. Furthermore, they will play a major role in enabling scientists

Fig. 1. The DELFIM Vehicle.

to actually program and follow the execution of missions at sea from the security and comfort of their laboratories.

The DELFIM craft is a small Catamaran 3.5 m long and 2.0 m wide, with a mass of 320 Kg, see Figure 1. Propulsion is ensured by two propellers driven by electrical motors. The maximum rated speed of the vehicle with respect to the water is 5 knots. The vehicle is equipped with on-board resident systems for navigation, guidance and control, as well as mission control. Navigation is done by integrating motion sensor data obtained from an attitude reference unit, a Doppler unit, and a DGPS (Differential Global Positioning System). Transmissions between the vehicle, its support vessel, the fixed GPS station, and the control centre installed on-shore are achieved via a radio link with a range of 80 Km. The vehicle has a wing shaped, central structure that is lowered during operations at sea. At the bottom of this structure, a low drag body is installed that can carry acoustic transducers, including those used to communicate with submerged craft. For bathymetric operations and sea floor characterization, the wing is equipped with a mechanically scanning pencil beam sonar and a sidescan sonar.

The paper addresses a number of theoretical and practical issues involved in the design, construction, and operation of the DELFIM vehicle at sea. Navigation system design was done by resorting to the theory of multi-rate and polytopic systems. The main goal of this research effort was to develop methodologies that could afford system designers with frequency-like design / analysis tools, thus extending to a time-varying, and even to a nonlinear setting, the highly practical and intuitively appealing filtering structures that are usually referred to as complementary filters [5],

This work was supported by the Portuguese FCT POSI programme under framework QCA III and by the project MEDIRES of the AdI.

[6]. For Guidance and Control, a new methodology was used that borrows from theory of gain-scheduled control systems exposed in [7], [8], [9]. At the Mission Control level, the work was focused on the development of software and hardware tools for mission programming and mission execution of autonomous vehicles, including cooperative control of surface and underwater vehicles. This work was instrumental in enhancing the capabilities of the Petri-net based software application named CORAL, proprietary of ISR/IST, originally described in [1]. At the same time, hardware architectures were developed for distributed real-time control of ocean robotic vehicles. Over the past few years, intensive series of tests at sea have shown the reliability of the overall Mission Control System (MCS) developed. The DELFIM ASC has by now completed a long series of seabed map building missions successfully, in a purely autonomous mode, under the supervision of its MSC. During a typical mission the vehicle performs a grid survey, executing path following maneuvers in the presence of shifting sea currents and wind, while collecting acoustic data from a sidescan and a mechanically scanning pencil beam sonar. The data are later processed to obtain high resolution bathymetric maps of the covered areas.

II. Navigation, Guidance, and Control

This section is an overview of the navigation, guidance, and control systems implemented on-board the DELFIM ASC. Guidance and control system design relied on a kinematic / dynamic model of the ASC. For navigation system design, a simple kinematic model was adopted. The organization of the section reflects the natural sequence of steps that were taken in the course of designing the above systems. Central to the design procedure is the development of a vehicle model that captures the kinematic equations of motion, together with inertial and hydrodynamic effects at a dynamic level.

A. ASC Model

The ASC model was derived from basic principles of physics that borrow from the theory of rigid body motion dynamics and kinematics; see for example [8] and [10]. System identification required a combination of theoretical and experimental methods to determine the most important hydrodynamic coefficients of the vehicle and the thruster characteristics. The estimated model for the DELFIM vehicle can be found in [11], which contains a description of the methodologies used for modeling and identification.

The equations of motion for surface vehicles can be obtained from Newton-Euler laws following the classical approach described in [10]. A simple derivation based on a general set-up adopted in robotics [12] can be found in [8]. Using that set-up, the equations are easily developed using a global coordinate frame $\{I\}$ and a body fixed coordinate frame $\{B\}$ that moves with the ASC. The following notation is required

$\mathbf{p} = [x, y]^T$ - position of the origin of $\{B\}$ expressed in $\{I\}$

$\mathbf{v} = [u, v]^T$ - linear velocity of the origin of $\{B\}$ relative to $\{I\}$, expressed in $\{B\}$

ψ - Heading angle that describes the orientation of frame $\{B\}$ with respect to $\{I\}$

r - body fixed angular velocity of $\{B\}$ relative to $\{I\}$, expressed in $\{B\}$

$\mathbf{R} = \mathbf{R}(\psi)$ - rotation matrix from $\{B\}$ to $\{I\}$, parameterized by ψ. $\mathbf{R}$ is orthonormal, satisfies $\mathbf{R} = I$ for $\psi = 0$, and can be written as

$$\mathbf{R} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix}.$$

The extended vector $\dot{\mathbf{q}} = [u, v]^T$ is obtained from the body fixed linear and angular velocity vectors. The input vector $\mathbf{n} = [n_{sb}, n_{ps}]^T$ consists of the differential and common mode of the speed of rotation of the main propellers. Let m and I be the mass and the moment of inertia of the vehicle, respectively. With this notation, the dynamics and kinematics of the ASC can be written in condensed form as

$$M_{RB}\,\ddot{\mathbf{q}} + C_{RB}(\dot{\mathbf{q}})\,\dot{\mathbf{q}} = \boldsymbol{\tau}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{n}) \quad (1)$$

$$\dot{\mathbf{p}} = \mathbf{R}(\psi)\,\mathbf{v} \quad (2)$$

$$\dot{\psi} = r \quad (3)$$

where $\boldsymbol{\tau}$ denotes the vector of external forces and moments. The symbols M_{RB} and C_{RB} denote the 2D rigid body inertia matrix and the matrix of Coriolis and centripetal terms, respectively. The vector $\boldsymbol{\tau}$ can further be decomposed as

$$\boldsymbol{\tau}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{n}) = \boldsymbol{\tau}_{add}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}) + \boldsymbol{\tau}_{body}(\dot{\mathbf{q}}) + \boldsymbol{\tau}_{prop}(\dot{\mathbf{q}}, \mathbf{n})$$

where $\boldsymbol{\tau}_{add}$ denotes added mass terms and $\boldsymbol{\tau}_{body}$ consists of the hydrodynamic forces and moments acting on the vehicle's body. The term $\boldsymbol{\tau}_{prop}$ represents the forces and moments generated by the propellers. The effect of a constant current can be simply modeled by re-writing the equations above in terms of relative velocity with respect to the water. In particular, the kinematic equation will yield

$$\dot{\mathbf{p}} = \mathbf{R}(\psi)\mathbf{v}_w + \mathbf{w}, \quad (4)$$

where $\mathbf{v}_w$ is the body-axis relative velocity of the ASC with respect to the water, and $\mathbf{w}$ is the water velocity in inertial frame $\{I\}$.

B. Guidance and Control

A number of missions with ASCs require the execution of trajectory tracking (TT) and path following (PF) maneuvers. Trajectory tracking refers to the problem of making a marine vehicle track a time-parameterized reference curve in two-dimensional space. This requires that the velocity of the vehicle be controlled with respect an inertial frame. In the case of an ASC faced with strong currents, a situation may arise where control authority is drastically reduced. Furthermore, trajectory tracking control often leads to jerky motions of the vehicle (in its attempt to meet stringent spatial requirements) and to considerable actuator activity. These problems are somehow attenuated when the temporal constraints are lifted, which brings us to the problem of path following. By this we mean the problem of forcing a vehicle to converge to and follow a desired spatial path, without any temporal specifications. However, we will still require that the vehicle track a desired temporal speed profile. The underlying assumption in path following control is that the vehicle's forward speed tracks the desired speed profile, while the controller acts on the vehicle's orientation to drive it to the path. Typically, smoother convergence to the path is achieved when path following strategies are used instead of trajectory tracking control laws, and the control signals are less likely to be pushed to saturation.

1) Trajectory Tracking: In a number of aeronautical applications, trajectory tracking controllers for autonomous vehicles have traditionally been designed using the following methodology. First, an inner loop is designed to stabilize the vehicle dynamics. Then, using time-scale separation criteria, an outer loop is designed that relies essentially on the vehicle's kinematic model and converts trajectory tracking errors into inner loop commands. In classical missile control literature this outer loop is usually referred to as a guidance loop. Following this classical approach, the inner control loop is designed based on vehicle dynamics, whereas the outer guidance law is essentially based on kinematic relationships only. During the design phase, a common rule of thumb is adopted whereby the inner control system is designed with sufficiently large bandwidth to track the commands that are expected from the guidance system (the so called time-scale separation principle). However, since the two systems are effectively coupled, stability and adequate performance of the combined systems are not guaranteed. This potential problem is particularly serious in the case of marine vehicles, which lack the agility of fast aircraft and thus impose tight restrictions on the closed loop bandwidths that can be achieved with any dynamic control law. Motivated by the above considerations, a new methodology was introduced in [7], [8], [9] for the design of guidance and control systems for marine vehicles whereby the guidance and control are designed simultaneously. The design methodology builds on the following results:

i) the trimming (equilibrium) trajectories of autonomous surface craft correspond to circumferences (that may degenerate into straight lines) parameterized by the vehicle's linear speed and yaw rate,

ii) tracking of a trimming trajectory by a vehicle is equivalent to driving a conveniently defined generalized tracking error to zero. A possible choice for the error space is given through the nonlinear transformation

$$\begin{cases} \mathbf{v}_e = \mathbf{v} - \mathbf{v}_c \\ r_e = r - r_c \\ \mathbf{p}_e = \mathbf{p} - \mathbf{p}_c \\ \psi_e = \psi - \psi_c \end{cases}$$

where the subscript c refers to conditions at equilibrium (vehicle moving along the trimming trajectory).

iii) the linearization of the generalized error dynamics about any trimming trajectory is time invariant.

Based on the above results, the problem of *integrated design of guidance and control systems* for accurate tracking of trajectories that consist of the juxtaposition of trimming trajectories can be cast in the framework of gain-scheduled control theory. In this context, the vehicle's linear speed and yaw rate play the role of scheduling variables that interpolate the parameters of linear controllers designed for a finite number of representative trimming trajectories. This leads to a new class of trajectory tracking controllers that exhibit two major advantages over classical ones: i) stability of the combined guidance and control system is guaranteed, and ii) zero steady state error is achieved about any trimming trajectory. Controller scheduling and implementation is done by using so-called delta-implementation [13]. Interestingly enough, with this strategy the structure of the final tracking control law is such that the trimming values for the plant inputs and for the states variables that are not explicitly required to track kinematic reference inputs are automatically "learned" during operation. The importance of this property can hardly be overemphasized, for it is in striking contrast with most known methods for trajectory tracking which build on the unrealistic assumption that all input and state variables along the trajectory to be followed are computed in advance.

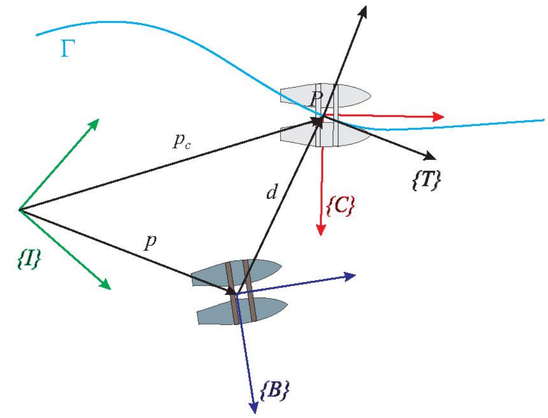

Fig. 2. Path following coordinate systems.

2) Path Following: Path following is the problem of making a vehicle converge to and follow a desired spatial path while tracking a desired speed profile. The temporal and spatial goals are therefore separated. Often, it is simply required that the speed of the vehicle remain constant. In what follows, it is generally assumed that the path is parameterized in terms of its length. A point on the path is therefore specified in terms of its curvilinear abscissa, denoted s. The solution to the problem of path following adopted for the DELFIM ASC is rooted in the work described in [14] for wheeled robots. When extended to marine robots, the key ideas explored can be briefly explained by considering Figure 2, which depicts the situation where a vehicle follows a two dimensional path denoted Γ.

A path following controller should compute i) the length of vector d from the vehicle's center of mass to the closest point P on the path (if this distance is well defined) and ii) the angle between the vehicle's total velocity vector and the tangent to the path at P, and reduce both to zero. Stated equivalently, the objective is to align the total velocity vector with x_T, where the latter is tangent to the path and is easily identified with the $x-$ axis of so-called Serret-Frenet $\{T\}$ frame at point $P(s)$. Clearly, x_T plays the role of the flow frame of a "virtual target vehicle" with body frame $\{C\}$ that should be tracked by the flow frame of the actual vehicle. The mismatch between the two frames (as measured by the linear distance and angle between the two) plays a key role in the definition of the error space where the path following control problem can be formulated and solved.

A solution to the problem of path following that relies on gain-scheduling control theory and on the linearization of a conveniently defined generalized error vector about trimming paths, akin to that previously described for trajectory tracking, is reported in [8]. See also [7] for an application of the same techniques to aircraft control.

C. Navigation

Navigation systems are essential to the operation of mobile robots that perform complex missions in autonomous mode. See [15], [16], [17], [18] and the references therein for a broad view of navigation system design methodologies in the ocean robotics area. Traditionally, navigation system design is done in a stochastic setting using Kalman-Bucy filtering theory [19]. For nonlinear systems, design solutions are usually sought by resorting to Extended Kalman filtering techniques.

If the sensors used in a navigation system are sampled at the same frequency, the corresponding filter operators are linear and time-invariant. This leads to a fruitful interpretation of the filters in the frequency domain. In the case of linear position and velocity estimation, however, the characteristics of global positioning systems such as the NAVSTAR-GPS imply that the position measurements are available at a rate that is lower than those of the remaining sensors installed on board. To deal with this problem a multi-rate complementary Kalman filtering design technique was developed for the DELFIM ASC. See [6] and the references therein. The ASC is equipped with the following motion sensors:

1) a *NAVSTAR GPS* (Global Positioning System) receiver that computes the latitude, longitude, and altitude in the WGS-84 datum. The GPS receiver, running advanced positioning algorithms, namely the Real Time Kinematics (RTK), can achieve centimetric accuracy in the fixed version and decimetric accuracy in the float version.
2) a *Doppler log sonar* that provides on-board referenced measurements $\mathbf{v}_w^m$ of body-fixed relative velocity vector $\mathbf{v}_w$.
3) An attitude reference that gives very accurate estimates of yaw angle ψ and respective angular velocity r.

Based on the coordinates provided by the GPS, after a suitable transformation to the local coordinate frame $\{I\}$, the position $\mathbf{p} = [x, y]^T$ becomes available. The Doppler data are simply converted from body to inertial reference frame to obtain measurements of relative velocity in $\{I\}$. The interrogation rates for the GPS and for the Doppler sonar are $2Hz$ and $4Hz$, respectively. The following specifications for the navigation system were set as guidelines for the design of a multi-rate complementary filter:

1) Obtain good estimates of the vehicle position and velocity;
2) Achieve a settling time of $240\,s$ on the estimate of the water current velocity.
3) Achieve a settling time of $6\,s$ on the position estimate.

The design model for the complementary navigation filter is easily obtained from the kinematic equations of the ASC, leading to two sets of decoupled equations that correspond to the two linear coordinates x, and y. For each coordinate, the design model is given by

$$\left\{\begin{array}{ll} \mathbf{x}(k+1) & = A(k)\mathbf{x}(k) + B_u(k)\mathbf{u}(k) \\ \mathbf{z}(k) & = C_z(k)\mathbf{x}(k) \\ \mathbf{y}(k) & = C_y(k)\mathbf{x}(k), \end{array}\right. \tag{5}$$

with $\mathbf{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$, where x_1 represents linear coordinate x or y and x_2 is an appended state aimed at estimating the corresponding component of the water velocity in $\{I\}$. In the model, the input $\mathbf{u} = \mathbf{R}(\psi)\mathbf{v}_w^m$ is the measured value of relative velocity of the vehicle expressed in $\{I\}$, $\mathbf{z}$ is an artificial observation vector that shapes the performance of the filter, and $\mathbf{y}$ is the vector of periodic observations. In the present application,

$$A(k) = \begin{bmatrix} 1 & h \\ 0 & 1 \end{bmatrix}, \quad B_u(k) = \begin{bmatrix} h \\ 0 \end{bmatrix},$$

$$C_y(k) = \left\{ \begin{array}{ll} \begin{bmatrix} 1, & 0 \end{bmatrix} & \text{if } k\, MOD\, 2 = 0 \\ \begin{bmatrix} 0, & 0 \end{bmatrix} & \text{if } k\, MOD\, 2 = 1 \end{array}\right. ,$$

and $C_z(k) = \begin{bmatrix} 1 & 0 \end{bmatrix}^T$. The periodic nature of the matrix $C_y(k)$ is obvious. For DELFIM, the observer feedback gains were obtained by solving a periodic $\mathcal{H}_2$ problem using Linear Matrix Inequalities (LMIs). The reader is referred to [6] for complete details on the design methodology that extends classical concepts of complementary filtering to a periodic setting.

III. Mission Control System

The previous sections described some of the techniques used for ASC control and navigation. In what follows we describe briefly how to transition from theory to practice. To do this, two key ingredients are needed: i) a distributed computer architecture, and ii) a software architecture for system implementation and human-machine interfacing. When implemented in a fully operational vehicle (equipped with the systems for navigation, guidance, and control, together with the remaining enabling systems for energy and scientific payload management, actuator control, and communications), the latter is often referred to as Mission Control System. For our purposes, a Mission Control System is simply viewed as a tool allowing a scientific end-user not necessarily familiarized with the details of marine robotics to program, execute, and follow the progress of single or multiple vehicles at sea. With the set-up adopted at IST/ISR, mission design and mission execution are done seamlessly by resorting to simple, intuitive human/machine interfaces. Missions are simply designed in an interactive manner by clicking and dragging over the desired target area maps and selecting items out of menus that contain a list of possible vehicle actions. See Figure 3, which is a printout of a graphical interface for mission design. Notice the presence of a mission map (map of the area to be covered) with obstacles to be avoided, together with a menu of the vehicles available to execute the mission that is being designed. Available to

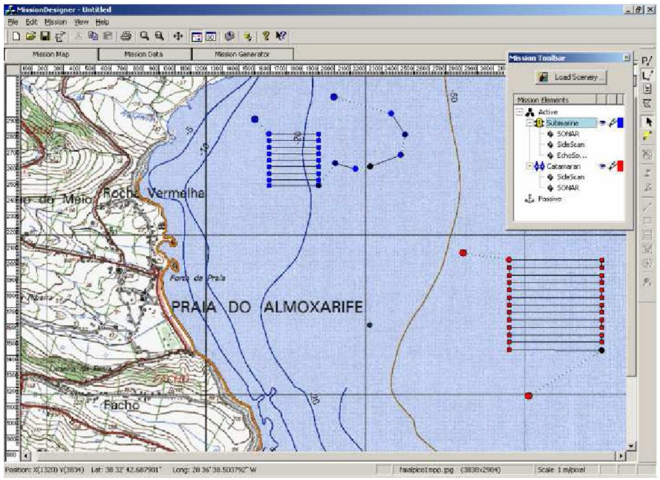

Fig. 3. Multiple vehicle mission design: graphical interface.

a mission designer are the functionalities of each vehicle (including the types of scientific sensors available), a set of mechanisms enforcing spatial / temporal multi-vehicle synchronization, and a path planning application to help in the mission design process (so as to meet adequate temporal /spatial / energy requirements).

The process of mission design and mission execution unfolds into four basis steps. First, the mission is designed using the graphical interface described above. A mission program is automatically generated in Step 2 and compiled in Step 3. Finally, the mission program is sent to the vehicle or fleet of vehicles in Step 4 and run in real-time. During program execution, the human operator follows the progress of the mission using a similar graphical interface, which now shows the trajectories of the vehicles as they become available via the inter-vehicle communications network.

The methodology adopted for Mission Control System design and implementation can be best explained in [20], [21]. The methodology builds on the key concept of Vehicle Primitive, which is a parameterized specification of an elementary operation performed by a marine vehicle (e.g., keeping a constant vehicle speed, maintaining a desired heading). Vehicle Primitives are obtained by coordinating the execution of a number of concurrent (Vehicle) System Tasks, which are parameterized specifications of classes of algorithms or procedures that implement basic functionalities in an ocean robotic system (e. g., the Vehicle Primitive in charge of maintaining a desired heading will require the concerted action of System Tasks devoted to motion sensor data acquisition, navigation and vehicle control algorithm implementation, and actuator control). Vehicle Primitives can in turn be logically and temporally chained to form Mission Procedures, aimed at specifying parameterized robot actions at desired abstraction levels. For example, it is possible to recruit the concerted operation of a set of Vehicle Primitives to obtain a parameterized Mission Procedure that will instruct a vehicle to follow an horizontal path at a constant speed, depth and heading, for a requested period of time.

Mission Program generation, and simplify the task of defining new mission plans by modifying/expanding existing ones. With the methodology adopted, System Task design is carried out using well established tools from continuous/discrete-time dynamic system theory while finite state automata are used to describe the logical interaction between System Tasks and Vehicle Primitives. The design and analysis of Vehicle Primitives, Mission Procedures, and Mission Programs, builds on the theory of Petri nets, which are naturally oriented towards the modeling and analysis of asynchronous, discrete event systems with concurrency. This approach leads naturally to a unifying framework for the analysis of the logical behavior of the discrete event systems that occur at all levels of a Mission Control System to guarantee basic properties such as the absence of deadlocks. A Mission Program is thus effectively embodied into a - higher level - Petri Net description that supervises the scheduling of Mission Procedures (and thus indirectly of Vehicle Primitives) concurring to the execution of a particular mission. The actual implementation of the building blocks referred above is done by resorting to a powerful Petri net description language named CORAL+ (proprietary of IST/ISR).

The Mission Control System developed is supported on a distributed computer architecture. Distributed processes (both inside a single vehicle or across several vehicles) are coordinated using inter-process/inter-computer communication and synchronization mechanisms implemented over CAN Bus and Ethernet, using Internet Protocol (IP) and other proprietary communication protocols. This distributed computer architecture is designed around PCs (PC104) running the Windows Embedded NT operating system, and around 8 and 16 bit microcontrollers (such as the Siemens C509L and the Philips XAS3) that communicate using the standard Intel 82527 Controller Area Network controller (CAN 2B protocol). All microcontroller boards were developed at IST/ISR with the purpose of meeting stringent requirements on power consumption, reliability, and cost.

IV. Test at Sea. Conclusions

The systems developed have been extensively tested at sea, with the ASC maneuvering in a purely autonomous mode under the supervision of its Mission Control system. Figures 4 through 6 illustrate the performance of the heading and path following controllers. The vehicle was operated at constant speed, under the influence of strong wave action. Figure 4 depicts the results obtained with the DELFIM ASC running simple yaw changing maneuvers. The performance of the path following controller is illustrated in Figures 5 and 6. These data were obtained while the DELFIM ASC performed a lawn mowing maneuver over a seamount, off the coast of Terceira Island in the Azores. In the mission, the ASC ran a path following algorithm along the longer transects, while fighting waves and the ocean current. Over the past years, the DELFIM ASC has been used extensively as a versatile tool to map the seabed in shallow waters. The systems developed have proven extremely reliable. The expertise acquired is steadily impacting on the development of other ASCs at the ISR/IST for a number of applications

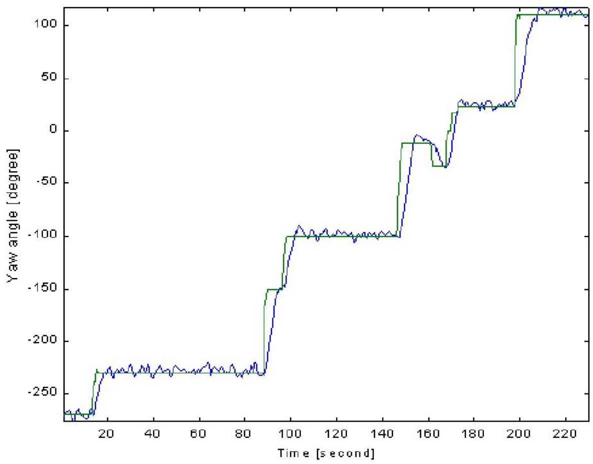

Fig. 4. Yaw command and vehicle response.

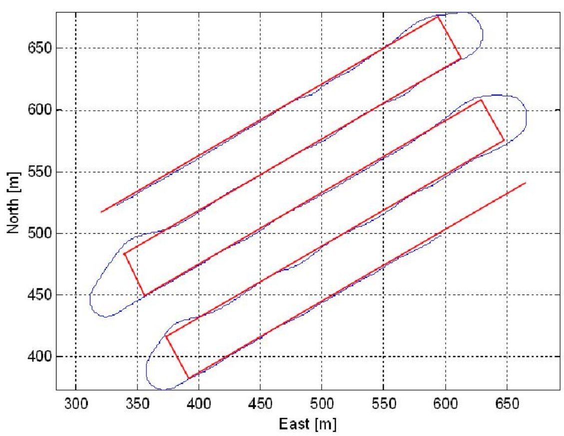

Fig. 5. Reference and actual vehicle paths.

that range from oceanographic surveys to the inspection of rubblemound breakwaters.

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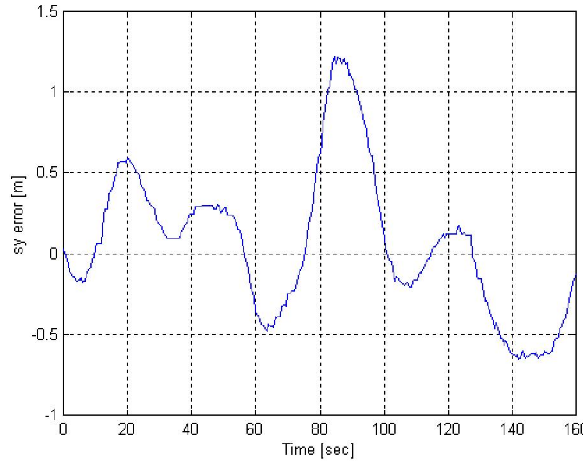

Fig. 6. Path following error.

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