VEHICLE AND MISSION CONTROL OF THE SIRENE UNDERWATER SHUTTLE [1]

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Abstract. The paper describes the design, implementation, and testing at sea of the vehicle and mission control systems of Sirene, an autonomous underwater shuttle for the automatic deployment of benthic stations down to depths of 4000 meters.

Keywords. discrete event systems, Petri nets, mission control, guidance and control, nonlinear control, underwater vehicles, dynamic modeling.

1. INTRODUCTION

A European team coordinated by IFREMER has recently completed the development of a prototype autonomous underwater shuttle vehicle named Sirene to automatically position a large range of benthic stations in the seabed down to depths of 4000 m. The vehicle was developed in the scope of the MAST-II European project DESIBEL (New Methods for Deep Sea Intervention on Future Benthic Laboratories), that aimed at comparing different methods for deploying and servicing benthic stations. The reader will find in (Brisset *et al.*, 1995; Rigaud *et al.*, 1998) a general description of the DESIBEL project. See also (Aguiar and Pascoal, 1997) for a theoretical study of the guidance and control systems of the Sirene.

This paper summarizes the contribution of the Instituto Superior Técnico (IST) to the DESIBEL project. Its mains focus is on the design and implementation of the systems for vehicle control and guidance, as well as on the mission execution logic that was designed to schedule and synchronize some of the vehicle systems for tele-operation and automatic landing.

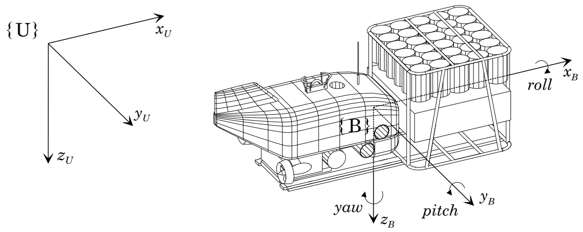

Fig. 1. *The Sirene coupled to a benthic laboratory. Body-fixed ({B}) and earth-fixed ({U}) reference frames.*

The paper is organized as follows: Section 2 introduces the Sirene vehicle and describes a typical mission scenario. Section 3 provides a brief summary of the control and guidance systems of the vehicle. Section 4 details the software and hardware architectures for control and guidance system implementation and describes their integration within the general system architecture developed by IFREMER. Section 5 describes a Petri net based approach to mission control system design. Finally, section 6 contains the experimental results obtained during a series of sea tests carried out by the French Agency IFREMER and the Instituto Superior Técnico (IST) off the coast of Toulon, France.

2. THE SIRENE VEHICLE. MISSION SCENARIOS

This section summarizes the main characteristics of the Sirene and describes a representative typical vehicle mission.

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2.1 *Vehicle characteristics*

The Sirene vehicle - depicted in Fig. 1 - has an open-frame structure and is 4.0 m long, 1.6 m wide, and 1.96 m high. It has a dry weight of 4000 kg and a maximum operating depth of 4000 m. The vehicle is equipped with two back thrusters for surge and yaw motion control in the horizontal plane, and one vertical thruster for heave control. Roll and pitch motion are left uncontrolled, since the metacentric height is sufficiently large (36 cm) to provide adequate static stability. In the figure, the vehicle carries a representative benthic lab that is cubic shaped and has a volume of 2.3 m^3. An acoustic link enables communications between the Sirene vehicle and a support ship for tele-operation purposes. At the core of the vehicle navigation system is a Long Baseline (LBL) positioning system developed by IFREMER (Rigaud *et al.*, 1998).

2.2 *Vehicle mission*

The main task of the Sirene vehicle is to transport and accurately position benthic laboratories at pre-determined target sites in the seabed. In a typical mission, the Sirene vehicle and the laboratory are first coupled together and launched from a support ship. Then, the ensemble descends in a free-falling trajectory (under the action of a ballast weight) at a speed in the range from 0.5 to 1 m/s. At approximately 100 m above the seabed, the Sirene releases its ballast and the weight of the all ensemble becomes neutral. At this point, the operator on-board the support ship instructs the vehicle to progress at a fixed speed, along a path defined by a number of selected way-points, until it reaches a vicinity of the desired target point. At this point the Sirene maneuvers to acquire the final desired heading and land smoothly on target, after which it uncouples itself from the benthic laboratory and returns to the surface.

3. GUIDANCE AND CONTROL.

This section introduces the dynamic model of the ensemble that consists of the Sirene and the associated laboratory, and describes its guidance and control laws. The reader is referred to (Aguiar, 1996; Aguiar and Pascoal, 1997) for complete details. In what follows, the ensemble will be referred to simply as the vehicle.

3.1 *General equations of motion*

Following standard practice, the kinematic and dynamic equations of motion of the vehicle were developed using a global coordinate frame $\{U\}$ and a body-fixed coordinate frame $\{B\}$, as depicted in Figure 1. The following notation is required (Fossen, 1994): $\eta_1 = [x, y, z]^T$ - position of the origin of $\{B\}$ measured in $\{U\}$; $\eta_2 = [\phi, \theta, \psi]^T$ - angles of roll (ϕ), pitch (θ), and yaw (ψ) that parametrize locally the orientation of $\{B\}$ with respect to $\{U\}$; $\nu_1 = [u, v, w]^T$ - linear velocity of the origin of $\{B\}$ relative to $\{U\}$, expressed in $\{B\}$ (i.e., body-fixed linear velocity); $\nu_2 = [p, q, r]^T$ - angular velocity of $\{B\}$ relative to $\{U\}$, expressed in $\{B\}$ (i.e., body-fixed angular velocity).

With this notation, the kinematics and dynamics of the vehicle can be written in compact form as

Kinematics

$$\begin{bmatrix} \dot\eta_1 \\ \dot\eta_2 \end{bmatrix} = \begin{bmatrix} {}^U_B R(\eta_2) & 0 \\ 0 & Q(\eta_2) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} \iff \dot\eta = J(\eta)\nu \qquad (1)$$

Dynamics

$$M_{RB}\dot\nu + C_{RB}(\nu)\nu = \tau_{RB} \qquad (2)$$

where ${}^U_B R(\eta_2)$ is the rotation matrix from {B} to {U} parameterized by the vector η_2 of roll, pitch, and yaw angles, and $Q(\eta_2)$ is the matrix that relates body-fixed angular velocity with roll, pitch, and yaw rates. The vector $\nu = [u, v, w, p, q, r]^T$ consists of the body-fixed linear and angular velocity vectors, and $\tau_{RB} = [X, Y, Z, K, M, N]^T$ is the generalized vector of external forces and moments. The symbols M_{RB} and C_{RB} denote the rigid body inertia matrix and the matrix of Coriolis and Centrifugal terms, respectively. The vector τ_{RB} can further be decomposed as $\tau_{RB} = \tau + \tau_A + \tau_D + \tau_R$, where τ_R denotes the term due to buoyancy and gravity and τ_A is the added mass term. The term τ_D captures the damping and lift effects, and τ represents the forces and moments generated by the thrusters.

To be of practical use, the general equations of motion must be tuned for the vehicle in study. The main difficulty lies in computing the term τ_{RB} that arises in the dynamics equation. In the present case, this was done using both theoretical and experimental methods, and by exploring the analogy with the *Dolphin 3K* vehicle (Nomoto and Hattori, 1986). The reader will find in (Aguiar, 1996; Aguiar and Pascoal, 1997) a description of the model parameters adopted based on a series of tests that were performed in a circulating water channel at the *VWS - Versuchsanstalt fur Wasserbau und Schiffbau*, Berlin with a quarter scale model of the vehicle. In the final model, the added mass and quadratic drag terms were decomposed as $\tau_A = -M_A\dot\nu - C_A(\nu)\nu$ and $\tau_D = -D(\nu)\nu$ respectively, where the hydrodynamic damping matrix $D(\nu)$ is strictly positive (Fossen, 1994). The vehicle model can then be written in compact form as

$$\begin{gathered} M\,\dot\nu + C(\nu)\,\nu + D(\nu)\,\nu + g(\eta) = \tau \\ \dot\eta = J(\eta)\,\nu \end{gathered} \qquad (3)$$

where τ is the vector of actuator control forces and moments, $g(\eta) = -\tau_R$, $M = M_{RB} + M_A$, and $C(\nu) = C_{RB}(\nu) + C_A(\nu)$. It is assumed that M is constant and positive definite, and that $C(\nu)$ is skew-symmetrical, i.e., $M = M^T > 0$ and $C(\nu) = -C^T(\nu) \quad \forall_{\nu \in \mathcal{R}^6}$. The model was used for dynamic simulations and control system design purposes.

3.2 *Control system design*

The main objectives of the control systems of the Sirene are to stabilize the vehicle and steer it in the in the horizontal and vertical planes. It is important to remark that since the vehicle is only equipped with one vertical thruster and two main back thrusters, there are a smaller numbers of actuators than degrees of freedom. To tackle this problem, it was decided to design separate controllers for speed, heading, and depth, and to leave roll and pitch passive (an altitude controller was also designed for the vehicle, but its structure is similar to that of the depth controller). Following this approach, the control variables used in the speed, heading, and depth control loops were the common mode and differential mode activity of the back thrusters, and the activity of the vertical thruster, respectively.

Control system design addressed the problems of vehicle stabilization and precise command following in the presence of large vehicle and actuator hydrodynamic parameter uncertainty. The importance of this issue can be hardly overemphasized, since it was expected that the some of the hydrodynamic parameters would differ from their estimated values by as much as 50%. The methodology adopted for control system design borrowed from sliding mode control theory, and led naturally to a controller structure that exhibits proportional, derivative, and integral terms, together with additional nonlinear terms that provide robustness against vehicle parametric uncertainty. The reader is referred to (Utkin, 1978) for an in-depth presentation of sliding mode control theory, and to (Fossen, 1994) for interesting applications in the area of underwater robotics. See also (Aguiar, 1996; Aguiar and Pascoal, 1997) for a thorough discussion of the design of the control systems for the Sirene vehicle. The simulation studies in (Aguiar and Pascoal, 1997) indicated that the types of control strategies developed were good candidates for real world applications. However, further work was required to transition from theory to practice and to actually implement the strategies developed in the computers installed on-board the Sirene vehicle. In particular, the problem of control system re-design in the absence of full state information had to be addressed and solved. This was done by simplifying the structure of the sliding mode controllers while retaining some of the nonlinear terms for robustness purposes. In the re-design process, the original sliding mode controllers played the role of benchmarks against which to compare the performance achieved with the new ones.

3.3 *Guidance system design*

The purpose of the guidance system is to generate references for the vehicle control systems so as to achieve adequate tracking of trajectories specified in a given reference frame. This requirement is important during the execution of transition maneuvers aiming at transferring the vehicle to the vicinity of the final target location. The guidance law (also referred to as XY-controller) implemented in the Sirene vehicle is standard: suppose that a flight maneuver is defined by a finite sequence of way points (x_k, y_k, z_k): $k = 1, \dots, N$. Assuming that the vehicle progresses at constant speed and that the depth coordinate is controlled independently, the line of sight guidance scheme computes reference commands

$$\psi_r(t) = \tan^{-1}\left(\frac{y_k - y(t)}{x_k - x(t)}\right) \tag{4}$$

for yaw, where the value of k is incremented when the vehicle reaches a *circle of acceptance* with radius ρ_0 centered at the next way point, i.e. when the vehicle location $(x(t), y(t))$ is such that

$$\rho^2(t) \;=\; [x_k - x(t)]^2 + [y_k - y(t)]^2 \;<\; \rho_0^2$$

Notice that in equation (4) care must be taken to select the proper quadrant for ψ_r. The modification of the above guidance law to deal with the presence of ocean currents is explained in (Aguiar and Pascoal, 1997).

4. MOTION SENSOR SUITE. COMPUTER HARDWARE AND SOFTWARE ARCHITECTURES.

For guidance and control purposes, the Sirene vehicle is equipped with the following sensor units:

1. Echosounder *Brooks* for altitude measurements.
2. Depth Cell *DC10R-C Transinstruments* for depth measurements.
3. Attitude reference unit *AHRS-C303 Watson Industries* to measure the angles of roll, pitch, and yaw and their rates.
4. Doppler log *TSM5740, Thomson* to measure the velocity of the vehicle with respect to the seabed.
5. Long baseline system (LBL), developed by *IFREMER*, to provide estimates of the position of the vehicle with respect to the seabed (Rigaud *et al.*, 1998)

The computer system devoted to guidance, dynamic control, and mission control system implementation runs the Microware OS9 operating system that allows for real-time multi-tasking and memory management and offers interprocess communication facilities that include shared memory, signals, and events. The computer system is built around a MPL68030 @ 25 MHz based EUROCARD board, supported on the GESPAC G96 bus. Data communications with the vehicle sensor units, the IFREMER computer (Rigaud *et al.*, 1998), and the vehicle actuators are ensured via RS232/RS485 serial links.

The corresponding software architecture is depicted in figure 2, where the following major building blocks can be identified:

Command and Report System - receives user commands (e.g. set-points and activation com-

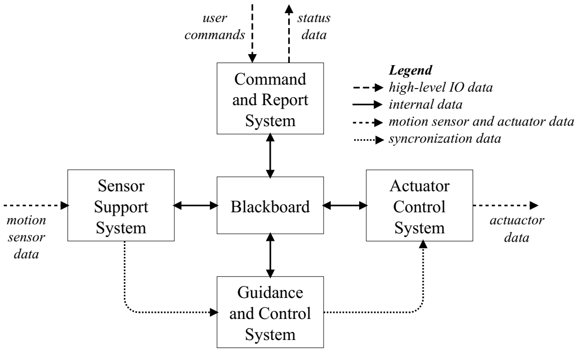

Fig. 2. Software system organization and data communication paths.

mands for the vehicle controllers) and reports the vehicle motion status to the blackboard. User commands and vehicle status data are sent through an acoustic communication link that provides a reliable, low data rate channel between the Sirene vehicle and the surface ship (Rigaud *et al.*, 1998).

Sensor Support System - manages the status of the motion sensors installed on-board the vehicle and samples their outputs at pre-defined rates. Motion sensor data include the estimates of the vehicle position provided by the LBL system of IFREMER (Rigaud *et al.*, 1998). When an internally defined sensor support system timer expires, the sensor data and their status are written in the blackboard and a synchronization signal is sent to the Guidance and Control System.

Guidance and Control System - implements the guidance and control algorithms for the vehicle. Each time a synchronization signal is received from the Sensor Support System, three actions are performed successively in time: i) control set-points and motion sensor data are read from the blackboard, ii) the actuation data for the Actuator Control System are computed and written in the blackboard, and iii) a synchronization signal is sent to the Vehicle Actuation System.

Actuator Control System - manages the status of the vehicle actuators and commands their activity in response to the actuation data provided by the Guidance and Control System. Each time a synchronization signal is received from the Guidance and Control System, actuation data are read from the blackboard and sent to the vehicle actuator drivers.

There is a one-to-one relationship between the main blocks in the figure and a specific set of real-time independent tasks that were implemented in the computer resident on-board the vehicle using the classic blackboard communication methodology. Task synchronization is achieved using operating system signal mechanisms. A set of commands is available to change the functionality of all the tasks.

5. MISSION EXECUTION LOGIC: A PETRI NET BASED APPROACH.

This section describes the mission execution logic (MEL) that was developed to: i) accept motion commands from an operator installed on-board the support ship, ii) synchronize and coordinate the operation of the basic vehicle systems that are required to execute those commands, and iii) enable emergency maneuvers when required. The set of basic commands available include those to engage and declare set-points for the yaw, depth, and altitude controllers, as well as to activate and specify a finite set of way points for the XY-controller in the horizontal plane. The speed of the vehicle is set by the operator, who specifies the common mode of the inputs to the back thrusters. The differential thruster activity is computed by the yaw controller. A specific command is also available to instruct the vehicle to land on the seabed by forcing it to track an altitude command signal that changes smoothly from an initial altitude value to zero.

During operations close to the seabed, the safety of the Sirene is of overriding concern due to possible terrain irregularities in the proximity of the landing site or the existence of unforeseen obstacles. It is up to the MEL to set the highest priority to the task of avoiding those obstacles.

The design and modeling of the mission execution logic for the Sirene was done by resorting to Petri nets, which are specially suited to capture the interplay between time-driven and event-driven systems. We assume the reader is familiar with the basic concepts of Petri net theory and its applications to the modeling of complex systems (Cassandras, 1993; Freedman, 1991). At their inception, Petri nets were first used to formally study the mechanisms of communications between asynchronous components of a computer system. Since then, they have found widespread use in the design and analysis of real-world systems in the areas of manufacturing, networking and software engineering, as well as in robotic applications, see for example (Cassandras, 1993; Freedman, 1991; Saridis, 1989) and the references therein. The reader is referred to (Oliveira *et al.*, 1996) for an introduction to these and related topics, as well as an introduction to the Petri Net based framework that was used to *model* and *implement* a Mission Control System for the MARIUS autonomous underwater vehicle.

The key ideas underlying the development of the mission execution logic for the Sirene can be simply explained with the aid of a simple example that describes how the synchronization and coordination of the systems in charge of steering the vehicle in the horizontal plane were achieved. In this situation, only the controllers for yaw and XY motion control can be recruited. For operational reasons, it was decided that the yaw controller should have the highest priority of execution. The Petri net that embodies the corresponding priority logic is depicted in figure 3, which

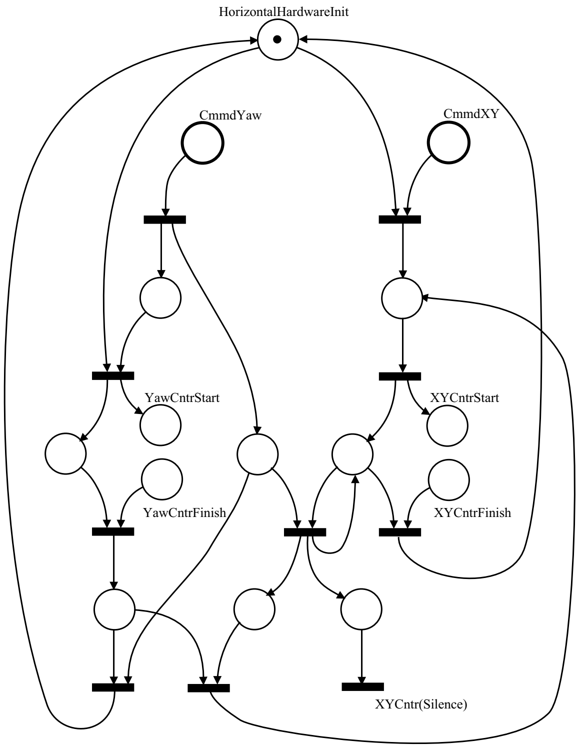

Fig. 3. A high-level system synchronization example using Petri Nets

should be examined together with figure 4.

The interaction with the human operator is modeled through a set of places in the Petri net that are drawn in bold. For example, the place labeled *CmmdYaw* is marked with a token whenever a signal to engage the yaw controller - issued by the operator through the acoustic communication link - is received on-board the Sirene. Suppose the Petri net is initialized with a token in the place *Horizontal/HardwareInit* and that *CmmdYaw* receives one token at a later time. Following the flow of execution of the Petri net, it is easy to see that the place *YawCntrStart* will be marked with a token. Close examination of the corresponding sub Petri net in figure 4 shows that the transitions *YawCntr(INIT)* and *YawCntr(ON)* will fire consecutively in time. The firing of transitions is the main mechanism for interaction with the systems described in section 4. For example, the firing of the transition *YawCntr(INIT)* will trigger a series of actions aiming at initializing the Guidance and Control System. Similarly, the firing of the transition *YawCntr(ON)* will engage the execution of a selected control algorithm. To disengage the yaw controller, a mark must be placed directly in *CmmdYawOff*. The transition *YawCntr(OFF)* will fire, causing a mark to appear in *YawCntrFinish* and consequently in the initial place *Horizontal/HardwareInit*.

The middle Petri net in figure 4 embodies the logic for emergency maneuvering. During mission execution, if the communications with the surface ship are lost, an unforeseen obstacle is detected, or the vehicle comes too close to the sea bottom, a token is automatically inserted in place *Horizontal-Silence*. and the transitions *YawCntr(SILENCE)* and *XYCntr(SILENCE)* will fire. As a consequence of the firings, commands will be issued to the Actuator Control System of figure 2 to drive the common and differential modes of the thruster inputs to zero. Should the vehicle recover from the emergency situation, the place named *NoSilence* will be automatically marked and the previous operation mode is recovered through the commands *YawCntr(NOSIL)* and *XYCntr(NOSIL)*.

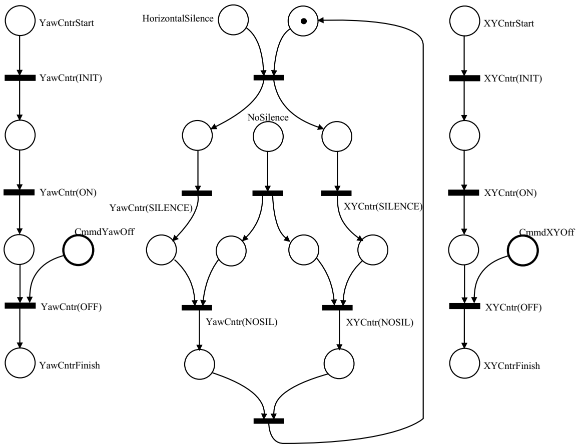

Fig. 4. Command of the Yaw and XY controllers in the horizontal plane.

6. EXPERIMENTAL RESULTS. TESTS AT SEA.

During the period from June until December 1997, a series of tests were carried out with the vehicle Sirene and a mock-up of a benthic laboratory off the coast of Toulon, France. During the tests, the performance of the guidance and control systems as well as the mission control logic for teleoperation and autonomous landing were fully assessed. The tests culminated with the landing of the vehicle at a depth of approximately 2200 meters. Figures 5, 6, 7 and 8 are but a small sample of the large amounts of experimental data that were obtained in the course of the test programme. Figures 5 and 6 show commanded and measured heading and depth, respectively. Figures 7 and 8 show the response of the vehicle to step commands in the inertial coordinates x and y. In the results shown, the vehicle positioning system relied on information provide by the long baseline (LBL) system and on vehicle thruster data. However, it did not use the Doppler unit to smooth out the position estimates between LBL updates. This explains the discontinuities observed in the measured positions.

Conclusions

The paper described the implementation and testing at sea of the control and guidance systems of the Sirene, an autonomous underwater shuttle for the automatic deployment of benthic stations down to depths of 4000 meters. The results obtained have paved the way for the development of a future generation of underwater shuttles that will endow end-users with the capability to au-

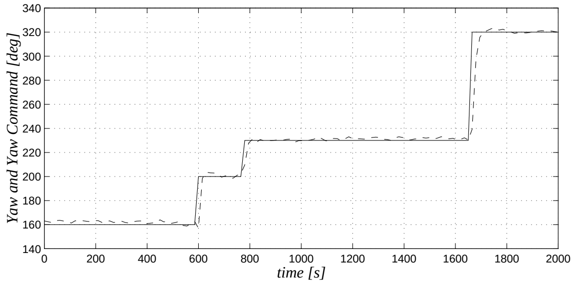

Fig. 5. Commanded and measured yaw angle.

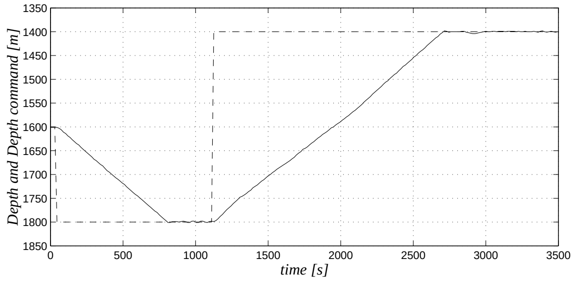

Fig. 6. Commanded and measured depth.

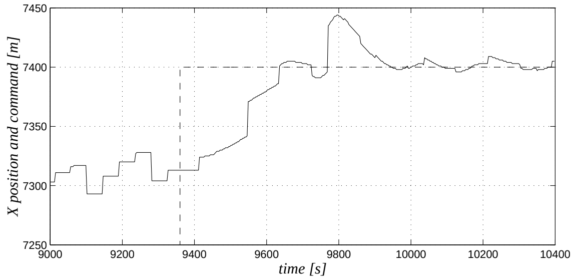

Fig. 7. Commanded and measured X position.

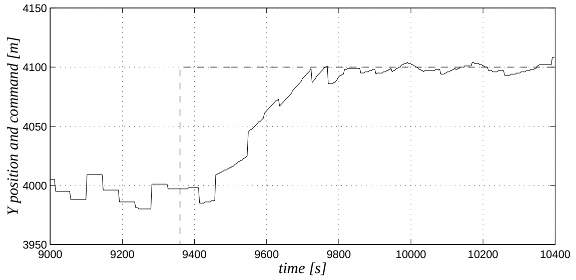

Fig. 8. Commanded and measured Y position.

tomatically deploy and service a large range of benthic laboratories.

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7. REFERENCES

Aguiar, A. (1996). Modeling, control, and guidance of an autonomous underwater shuttle for the transport of benthic laboratories. Master's thesis. Department of Electrical Engineering, Instituto Superior Técnico. Lisbon, Portugal.

Aguiar, A. and A. Pascoal (1997). Modeling and control of an autonomous underwater shuttle for the transport of benthic laboratories. In: *OCEANS-97*. Halifax, Canada.

Brisset, L., M. Nokin, D. Semac, H. Amann, W. Shneider and A. Pascoal (1995). New methods for deep sea intervention on future benthic laboratories: analysis, development, and testing. In: *Proceedings of the Second Mast Days and Euromar Market.* number 2050. Sorrento, Italy. pp. 1025–1037.

Cassandras, C. (1993). *Discrete Event Systems. Modeling and Performance Analysis.* The Aksen Associates Series in Electrical and Computer Engineering.

Fossen, T. (1994). *Guidance and Control of Ocean Vehicles.* John Wiley & Sons. New York, USA.

Freedman, P. (1991). Time, Petri nets, and robotics. *IEEE Transactions on Robotics and Automation* **27**(RA-4), 417–433.

Nomoto, Masao and Mutsuo Hattori (1986). A Deep ROV "DOLPHIN 3K": Design and Performance Analysis. *IEEE Journal of Oceanic Engineering* **OE-11**(3), 373–391.

Oliveira, P., A. Pascoal, V. Silva and C Silvestre (1996). Design, development, and testing of a mission control system for the MARIUS AUV. In: *Sixth International Advanced Robotics Program IARP–96.* Toulon, France.

Rigaud, V., M. Drogou, J. Obderdecke, C. Marfia, A. Pascoal, P. Oliveira, C. Silvestre (1998). DESIBEL: the SIRENE free swimming vehicle for the management of benthic stations. In: *Seventh International Advanced Robotics Program IARP–98.* Lafayette, Louisiana, USA.

Saridis, G. (1989). Analytical Formulation of the Principle of Increasing Precision with Decreasing Intelligence for Intelligent Machines. *Automatica* **25**(3), 461–467.

Utkin, V. I. (1978). *Sliding Modes and Their Application to Variable Structure Systems.* MIR Publishers. Moscow.