

# DESIBEL : The Sirene free swimming vehicle for the management of benthic stations

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Amongst the tools at the disposal of the scientific community, benthic laboratories and benthic stations are going to experience an increasing interest on account of the missions they will permit : observation, measurement and long term experimentation completed on the sea floor.

The project presented in this paper deals with the operation of future benthic laboratories and stations. Four different concepts were studied in the DESIBEL European project supported by the MAST EC program: a mobile hook, a dedicated ROV, the scientific ROV6000 VICTOR and a free swimming vehicle named SIRENE operated via an acoustic link. For each concept engineering studies were conducted , and comparative studies of dynamic behaviour and acoustic performances were carried out. In some cases equipment or mock-up were realised and tested at sea. This paper will describe SIRENE AUV operated through acoustics and the main technological advances in precise navigation and control through the acoustical link.

## 1- Introduction

The use of benthic stations become more and more important in the future scenario for deep-sea monitoring, to investigate the variability of ocean floor parameters in space and time[1].

For those new equipment's precise positioning (« metric ») is required, as well as possible intervention in the wide scope including handling or monitoring tasks, requiring « human control ». In a first analysis the control scheme is at least teleoperated. The level of teleoperation is depending of the kind of media used to communicate with the submerged system.

In the MASTII DESIBEL project a consortium leaded by IFREMER, composed of THETIS GmbH , VWS GmbH and GEOMAR GmbH in Germany and Insituto Superior Technico from Lisbon university in Portugal, had compare analytically, in simulation and at sea four concepts of benthic station handling and management.

The concepts investigated were [2] :

- an active docking system with a mobile hook (LOMOS).
- an active docking system with a special ROV (REMORA).
- a deep sea scientific ROV (ROV 6000- VICTOR).
- a free swimming vehicle (FREE MODULE- SIRENE).

This paper described the system and the operational results for the operations with the free swimming AUV SIRENE teleoperated by acoustics and developed by IFREMER with the support of IST for the guidance and control hardware and software.

## 2- General description of the SIRENE AUV

The free module SIRENE [3] (Fig 1 and 2) is designed to land a station with a metric relative positioning by 4000m depth, with a very precise, metric, accuracy. The vehicle is tele-supervised through a bi-directional acoustic link.

SIRENE is a 4 tonnes free swimming shuttle positioned through an hybrid acoustic long baseline, dead-reckoning system board on the vehicle itself.

The main **Dimensions** of the vehicle are the following :

Length: 4 metres

Width: 1,40 metres

Height: 1,70 metres

Displacement: 4 metric tons

The vehicle built in part with space parts of the CYANA IFREMER submersible (Propulsion) is rated to dive at 4000m depth. The vehicle is fitted with 2 main propellers and a vertical propeller (3\*2KW) and the power supply is assured with a 120V, 185Ah lead acid batteries within oil for pressure compensation.

**Communications** between the bottom and the surface or in surface are assured respectively by a new 10-12kHz, Chirp 20 bits/sec acoustic bi-directional teletransmission (« TcTm ») and a classical UHF radio transmission (19200bits/sec).

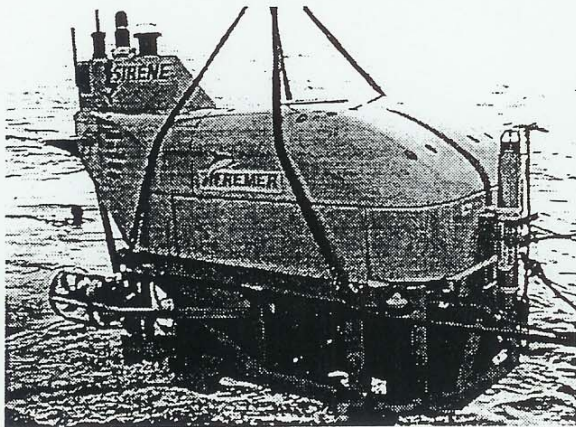


Fig1: Launching SIRENE



Fig2: SIRENE surfacing after a dive- View on GPS, TcTm transducer and radio antenna on the rear tail

**Positioning control and guidance** are built and assured on board the vehicle with the following set of sensors:

- i) Echosounder – Brooks for altitude measurements.
- ii) Depth Cell DC10R-C – Transinstruments for depth measurements.
- iii) Attitude reference unit AHRS-C303–Watson Industries for measurements of roll, pitch, and yaw angles and respective rates.
- iv) Doppler TSM5740, Thomson for measuring the velocity of the vehicle with respect to the seabed or in water track mode with respect to the water.
- v) GPS for initialisation of the navigation process on the surface and vehicle recovery after the dive
- vi) An electric current sensor that allows to estimate the propulsion effort, and to estimate pseudo-speeds of the vehicle
- v) Long baseline system: The heart of SIRENE's positioning system is an acoustic rangemeter that determines the distance between the vehicle and acoustic transponders. The measured ranges are individually validated by a consistency test that is based on the actual vehicle position estimate. This estimate is obtained from the measured vehicle displacement since a previous position. The detection/selection of range measurements ensures that erroneous data are rejected at the lowest possible level - this means that severe selection methods can be used and, at the same time, a maximum number of information are kept for the position update algorithm.

A specific rangemeter which represents the source of information relative to absolute references, allowing to update a driftless position estimate. It registers up to ten responses to the 16 KHz interrogation signal. It operates a maximum number of 6 beacons. The resolution is small relative to errors due to the CTD profile and beacon calibration. The rangemeter is the basic element of a Long - Baseline (LBL) positioning system or, in our case, the integrated autonomous position estimator.

An essential new feature has been introduced in the rangemeter. Most existing systems use a threshold detection that chooses the first strong response in a given time window - wrong detection due to noise, multipath etc. is frequent in this case. The new rangemeter detects up to 10 "candidate" ranges. In operation the maximum range is about 6000m. The selection of the "best" candidate range is accomplished by state-of-the-art data association techniques.

### **3- Handling of the Benthic Station and typical mission with SIRENE**

The free module and the station are linked together through electromagnets which stick steel parts fixed on the station's side to avoid to increase its height (Fig 3). The station has always a positive weight (heavy) and SIRENE has always a negative weight (light). The assembly of the 2 vehicles is neutral weight. For the dive, SIRENE is fitted with a releasable ballast used for descent, and another releasable ballast for the final ascent. These ballast's are calculated so that SIRENE can reach its final position during descent to save time and power.

During most of the descent phase, the station/module assembly has a positive weight and a neutral weight during displacement on the seabed. During the ascent, the station is naturally heavy to stay on the sea bottom and the module becomes light after it disconnects itself from the station.

The main phases of the SIRENE mission consist of:

- the launching of the assembly SIRENE/Station assembly
- steering the assembly SIRENE/Station to a desired position on the sea bottom up to depth of 4000m
- rotating the the SIRENE/station assembly to a desired heading
- deposit of the station at the selected target location
- returning the SIRENE return to the surface
- returning the SIRENE to the support vessel through radio teleoperation
- recovering SIRENE.

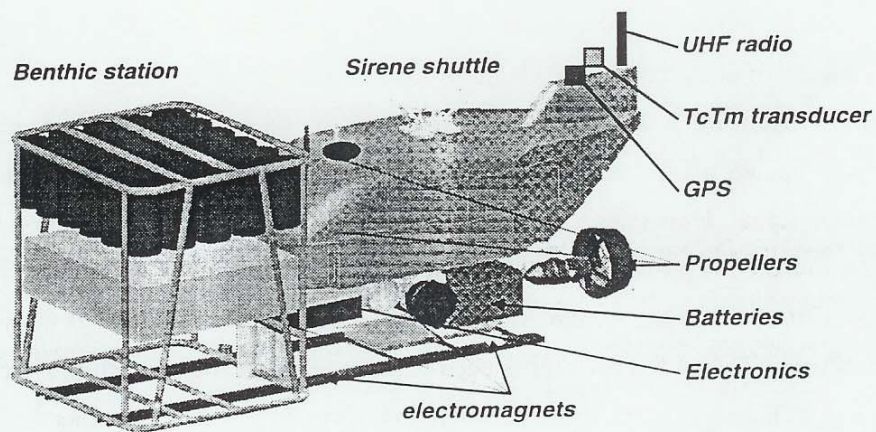


Fig3 The SIRENE concept for Benthic station handling

#### 4- Remote control / Acoustic telemetry (TC/TM)

The SIRENE is controlled (Tele-Control) and supervised (Tele-Measurement) from the surface vessel through an acoustic link.

The remote control / telemetry system is a bi-directional remote control, adapted from ORCA Corp. Standard Multiplication Modems [4] . The system consists of two acoustics transponder. The vehicle transducer is mounted on SIRENE and the surface transducer is integrated in a towed fish (15meters depth). The system central frequency is 11kHz a and the associated band is 2kHz. The initial operational specifications lead to work in 6000-meters depth (8000-meters oblique distances) , to be compatible with the environment (vessel, module) and with the acoustic positioning system classically used by IFREMER which is an « Oceano Instruments » LongBaseline system( 10-14kHz). As a consequence we have chosen a « secure » Chirp modulation which get 20Bits/sec. The initial

range specifications were verified at sea in oblique/slant range conditions by 2000m of depth. Other coding modes were envisaged at the beginning of the project but the operational scenario, and the obliquities specification led us to adopt the Chirp mode. An initial BPSK mode with a 2400 bits/sec well known by IFREMER and ORCA for image transmission from the Bottom, and alternative Frequency Hopping mode at 200 bits/sec were not chosen for the application.

The acoustic module integrate also a Range Measurement function, for long baseline positioning. Two acoustics transducers fixed on the top (Upper base) and on the bottom ( Lower base) of the vehicle are used for the TC/TM function and for the Range-Measurement function.

The SIRENE interrogate the LBL beacons at 16Khz during 10ms. Then Each LBL beacon replies at its own frequency between 10 and 14kHz with a 0.5 kHz step during 10ms. The vehicle is capable of measuring on board up to 10 echoes that may be used in the LBL trilateration calculus ( Direct, reflected on the surface , on the bottom, noise ,.. Echoes). The TcTm acoustic remote link is split in a bottom up link(Tm) and a top down link (Tc).The (Tm) Link duration is 14sec which allows to recover all the data coming from the vehicle including sensors , states and alarms.

The Tc down link is of variable duration from 4 to 8 sec in order to transmit piloting orders to the vehicle. On the surface vessel a « MASSA » acoustic module is integrated in a towed fish. This fish is submerged at 15m from the surface, to avoid surface noises ( Ship, sea state ...).

On the vehicle the TC/TM function is always assure by the upper acoustic transducer. The chronogram associated to the management of TC/TM and RM functions is show below.

Synchronisation between all the acoustics systems is done through a surface synchronous clock.

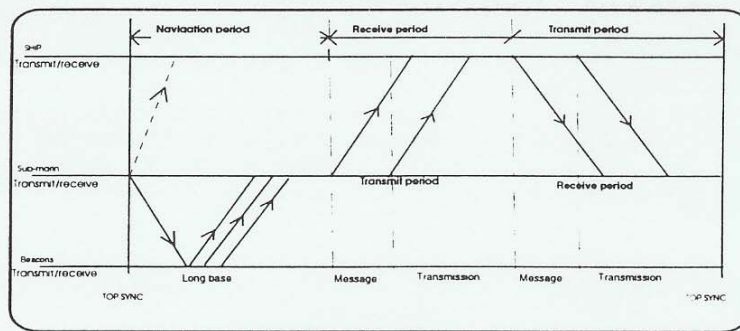


Fig 4 Chronogram

With the chirp modulation, the false transmission ratio is around 4% for the « bottom up » link for a 14 seconds signal and around 6% for the « top down » link for a 4 to 8 sec signal duration. The TcTm is also very robust to multiple signals and has been validated also by small depths. the behaviour of the system has been proven for oblique transmission up to 60 degrees to the vertical and the maximum range validated at sea to 6000m and simulated up to 9000m by limiting the emission power through the hardware in real conditions. The teletransmission has been used during the tests with the vehicle propulsion working.

*The positioning system is compatible with remote control / telemetry control.*

## 5- Positioning of SIRENE

The vehicle position is obtained in a local co-ordinate frame relative to the reference beacons. This simplification has been chosen in order to achieve the highest possible repeatability in a given beacon field. The technical characteristics of SIRENE have a direct impact on the vehicle navigation :

1. **the interlaced mode of the acoustic functions *range measurement and data transfer*** translates by a relatively long recurrence period (40 s) for the acoustic equipment. When displacement data are unprecise or erroneous, the dead-reckoning process accumulates a considerable error of the position estimate. The choice of the most probable range measurement to a reference transponder then becomes a difficult task.
2. **The calibration of the acoustic positioning system**, i.e. the determination of transponder positions and of the temperature/sound velocity profile is the most limiting factor in the precision balancing. The varying transponder configuration related to range validations, may lead to "jump" - errors in the estimated vehicle trajectory. This problem will be discussed in the presentation of sea-trial results, and solutions are proposed for future work.

The positioning algorithm uses a state space representation and applies *extended Kalman filtering*. The number of estimated parameters (16) is considerably high, and in order to avoid long computation times as well as the risk of numerical instability, we have chosen to divide the set of estimated parameters into four separate groups.

The first one comprises the horizontal UTM-coordinates  $x$  and  $y$ , the longitudinal and transversal speed  $v_l$  and  $v_t$ , the scaling factor of the static speed model, and horizontal current in axes  $x$  and  $y$ .

The second sub-state regroups depth  $z$  and the vertical velocity  $v_z$ . The depth is estimated from the pressure sensor in conjunction with a salinity profile. The use of an estimator algorithm for these quantities is justified only by the functions of coherence testing and of outlier rejection.

The third sub-system consists of heading and attitude angles roll and pitch. The three quantities are directly measured by the WATSON inertial vertical reference unit . The use of an estimator algorithm for these quantities is justified only by the functions of coherence testing and of outlier rejection.

The fourth sub-system is made up from the (position) biases of the acoustic beacons - one bias is attributed to each transponder. The estimation of these parameters allows a significant reduction of the RMS error in the range based positioning algorithm. The bias identification is only run when redundant range information is present. Theoretically, the biases vary with the vehicle position ("point of view"), and the convergence of the estimator is not guaranteed. In all dives of SIRENE, however, no problem has occurred with the estimator.

The detection of more than one candidate response for range results in the need for a sophisticated data association filter, that selects the most probable direct range. Several criteria are applied, in a hierarchical manner, to achieve reliable selection of the correct range.

The first criterion is coherence with the assumed vehicle position. The range which comes closest to this position is validated. A second criterion is the detection of a pair of direct/indirect responses in one set of range candidates. The direct range from such a pair is overrunning, if different, the range candidate from the first association level. If a series of direct/indirect range pairs is tracked, a new continuous element of this series is the highest qualification a range can get.

The confidence attributed to a range can be chosen according to the level of qualification from the association process. The higher the qualification of a range, the smaller we set its measurement variance in the extended Kalman filter - and the more significant will be its influence on the updated vehicle position estimate. Exceptions are defined for the positioning algorithm that are based on processor interrupts (divide by zero ...), numerical criteria for filter convergence, timer watchdogs that detect absence of data or continued data rejection and finally acoustically received user commands. These exceptions are processed by a supervisor program, that executes the appropriate action (partial or complete re-initialisation, recovery from earlier state, ...).

### Sea-Trials Results

19 dives were carried out during three missions on board the IFREMER's Suroit R/V in June, September and November 1997 in the Mediterranean sea. We illustrate below some representative dives.

The ESSIR1-2 dive has been undertaken in a low depth work-zone and illustrate **the dead-reckoning performance**. The maximum depth is 200m. We illustrate in this dive a thruster-current based dead-reckoning procedure. After the descent, three distinctive legs have been conducted : various speeds at constant heading at (1), high speed at constant heading (2) and low speed at constant heading. Between legs (1) and (2), some manoeuvring has been done that is not taken into account by the dead-reckoning algorithm. The dimensioning of the electric current vs. velocity profile seems to be

reasonable in legs (1) and (3), whereas the speed is too low in the second leg. The velocity profile would have to be adjusted in the upper section. Some considerable deviation in the third - low velocity- leg is not followed by the dead-reckoning track - these deviations are due to current or to strong variations of thruster commands that try to maintain the constant heading at low speed - indeed, the vehicle heading is approximately constant.

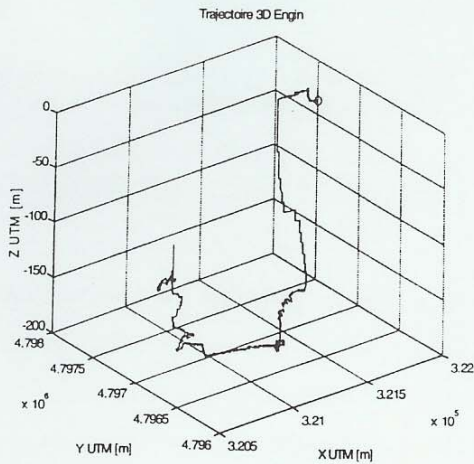


Fig5: 3D path

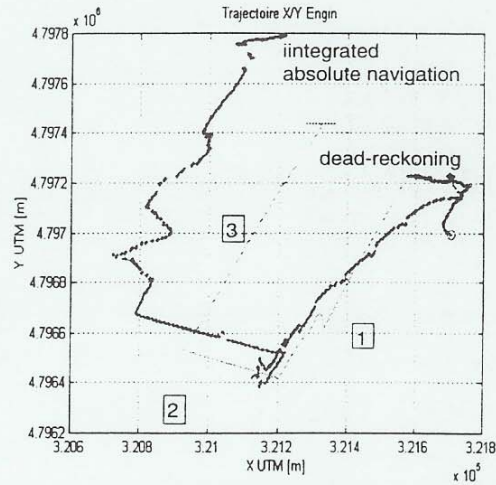


Fig 6: 2D path

The dive ESSIR2\_4 is a typical example for the SIRENE trials with a maximum depth of around 2000m and a duration of 5 hours which illustrate the **range bias estimation**. The beacon field was not calibrated accurately : the algorithm does not manage to validate ranges of all four beacons at the same time, some sharp 'steps' (~10m) occur in the vehicle trajectory when the set of validated beacons varies. The root mean square (RMS) range residual is important (~25m) in the case where range biases are not identified (figure 7,8 and 9). With use of the range bias estimator it is reduced - after convergence - to a significantly lower level (<10m). Some spikes in the RMS are due to the fact that with biases identified, ranges are becoming more consistent and all four beacons can be taken into account. Near the end of the dive the RMS increases slightly: the vehicle is loosing depth and the range biases identified in the horizontal plane are changing as the vertical projection gets important.

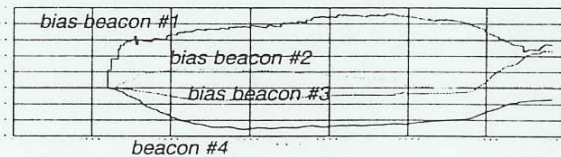
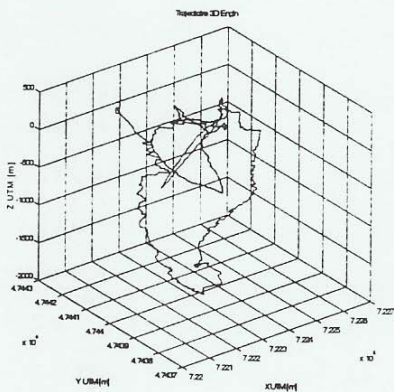
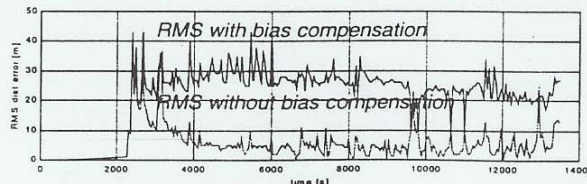


Fig 8 : Range biases bias





The ESSIR2\_5 dive reaches a maximum depth of 2270m, where the vehicle landed on the sea-floor (figure ....) and illustrate the **range selection**. The Beacons field and calibration is the same as in trial ESSIR2\_4. The rangemeter was adjusted to an increased sensibility, resulting in a high number of erroneous response detection's. Figure 11 and 12 shows all measured and the validated ranges (complete two way range) for beacons #1 and #2. The position estimator tracks correctly the 'right' distances for beacon #2, whereas it 'looses' some measurements of beacon #1 which has a larger calibration error. The *indirect* ranges, which correspond to surface reflected signals, can clearly be distinguished as a second line of continuous ranges (figure 11).

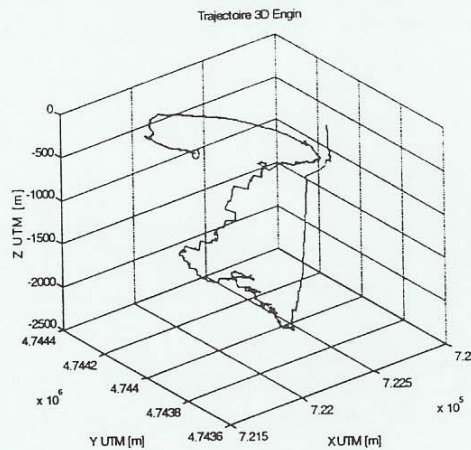


Fig 10: 3D vehicle path

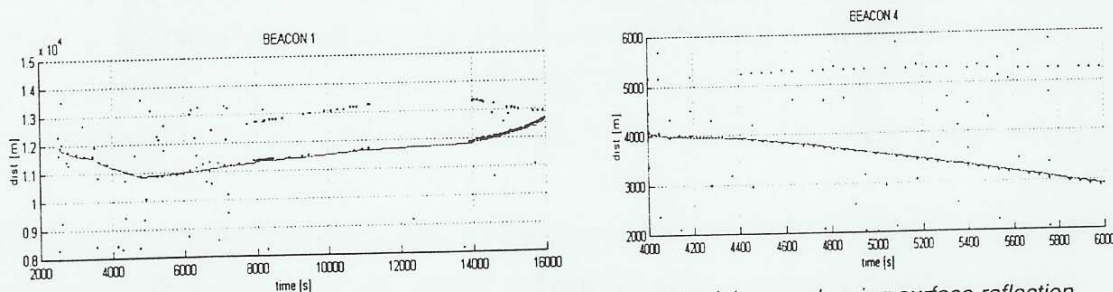


Fig11 and 12 validated ranges (Continuous line) / Raw ranges (points) / zoom showing surface reflection

### 6. Guidance and Control of the SIRENE vehicle

This section focuses on the development of the guidance and control systems for the SIRENE vehicle. The algorithms for control and guidance are briefly described, and the hardware and software modules for their implementation are presented. The section concludes with a description of experimental results obtained during a series of sea tests carried out by IFREMER and the Instituto Superior Técnico (IST) off the coast of Toulon, France.

**System Design.** The guidance and control systems of SIRENE are responsible for steering the vehicle through the different phases of a typical mission scenario in response to high level commands for heading, depth, or tracking of reference trajectories. Since only one vertical and two back thrusters were available, it was decided to design separate controllers for heading and depth, thus leaving roll and pitch passive. In all cases, sliding mode theory was used to achieve robust control in the presence of vehicle parameter and actuator uncertainty. Tracking of a reference path in the horizontal plane was achieved by combining the control loop for heading with a simple line-of-sight guidance scheme. An additional controller was developed for bottom following in the vicinity of the seabed, during the final landing phase. The reader will find in [6] complete details on the design of the vehicle's guidance and control systems. For a description of the vehicle's hydrodynamic model based on tests performed in a water circulating test at VWS, Berlin, Germany, see [7].

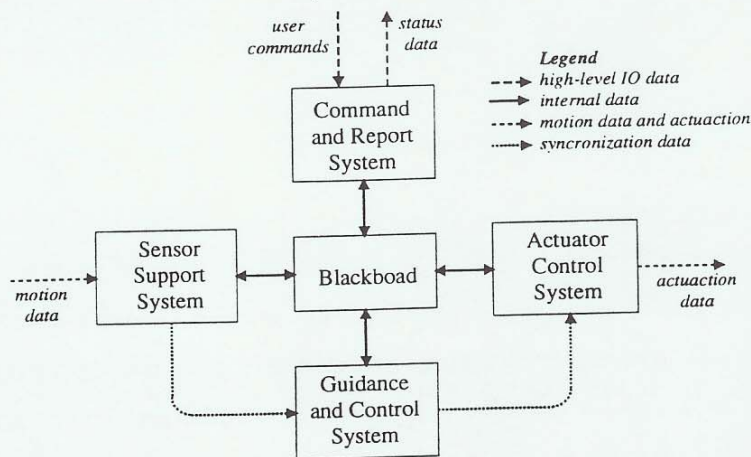


Fig 13 : Software systems organization and data communication paths

**System implementation: computer software, hardware.**

Figure 13 depicts the software organization of the IST computer on-board the vehicle SIRENE. A set of real-time independent tasks were implemented using the classic blackboard communication methodology. The tasks synchronization was achieved using operating system signal mechanisms and a set of commands is available to change the task functionality. A brief of the tasks follows:

*Command and Report System* - receives the user commands (e.g. setpoints and activation commands for the controllers) and reports the vehicle status in what the motion status using data resident in the blackboard.

*Sensor Support System* - manages the operational status of the sensor suite and samples the sensors at pre-defined rates. Sampled and status sensor data are written in the blackboard. Should the control system timer expire, the required data are updated 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. Each time a

synchronization signal is received, the setpoints and the motion data are read, the actuation data are computed and written in the blackboard, and a signal is sent to the Vehicle Actuation System.

*Actuator Control System* – manages the actuators status and commands their activity. Upon reception of a synchronization signal, data are read from the blackboard and sent to the actuators.

The IST computer runs the Microware OS9 operating system, which allows for real-time multi-tasking, memory management, and offers interprocess communication facilities that include shared memory, signals, and events. The computer system chosen is built around a MPL68030@25MHz based EUROCARD board, supported on the GESPAC G96 bus. The data communications with the sensor units, computers, and actuators was done using RS232/RS485 serial links.

Besides its role in implementing the guidance and control of SIRENE, the IST computer is also in charge of managing sensor acquisition, surveying battery status and performing propeller actuation. At the same time, it communicates with The IFREMER computer that is in charge of determining the vehicle position, managing security issues and controlling the dialogue between the vehicle and the surface. The two computers are linked with a simple RS232 link. This simplified the final integration phase and proved sufficient in view of the low bandwidths required for communications.

**System implementation: software organization and high-level synchronization.**

The implementation of the systems described above required the development of specialized software modules that capture the interplay between time-driven and event-driven systems as embodied into specific Petri net structures, see [8] and references therein. As an example, Figure 14 represents the Petri net associated with the Yaw and XY commands, which is briefly explained below.

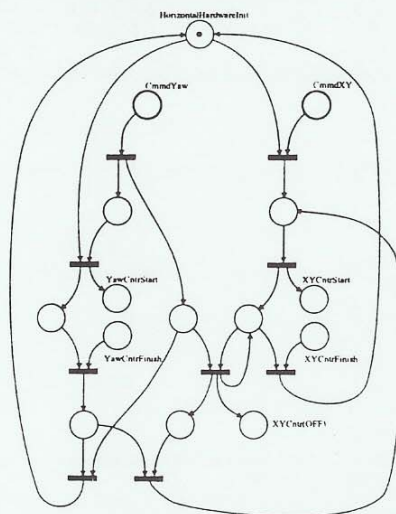


Fig 14- A high-level system synchronization example using Petri nets.

The Petri net depicted in Figure 14 describes the synchronization mechanism and the required priority rule among the yaw and XY controllers. In this case the yaw controller has the higher priority and can be activated by the vehicle operator. Places *CmmdYaw* and *CmmdXY* that drive the behavior of the net are directly marked by surface commands. In general marks in the places represent operational status of the tasks involved.

### Experimental results. Tests at Sea.

During the series of tests were carried out with the vehicle SIRENE and a mock-up of a benthic laboratory, the vehicle was landed in a fully autonomous mode at a depth of approximately 2200 meters. Figures 15, 16, 17 and 18 are about a small sample of the large amounts of experimental data that were obtained in the course of the test programme [7]. Figures 15 and 16 show commanded and measured heading and depth, respectively. Figures 17 and 18 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 a long baseline system (LBL) 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*

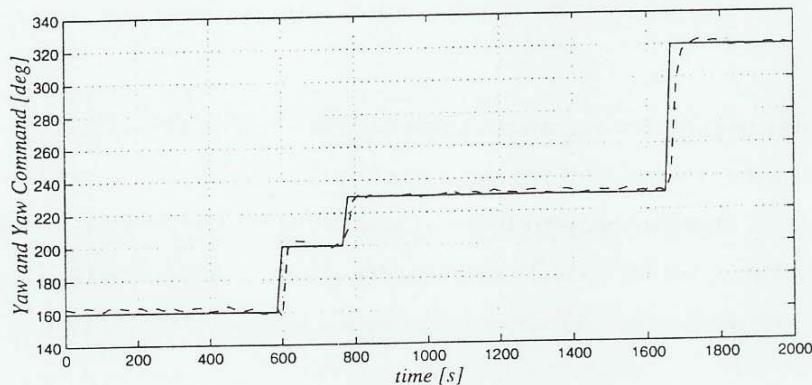


Fig15 Commanded and measured yaw angle

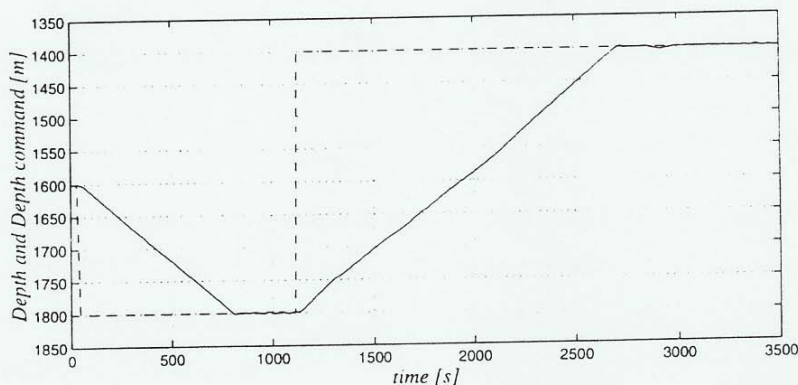


Fig16 Commanded and measured depth

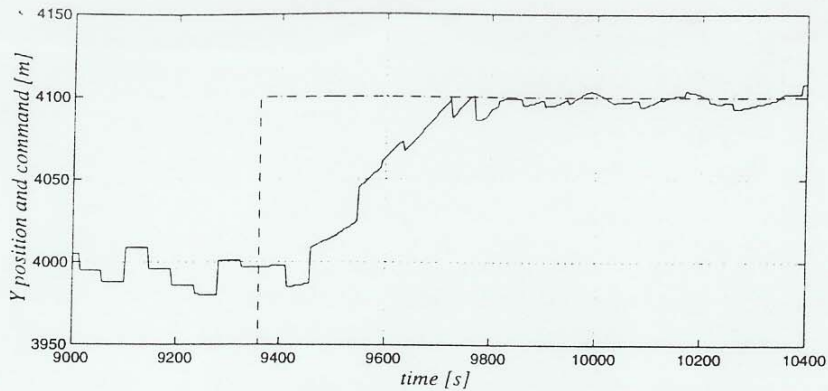


Fig17: Commanded and measured X position

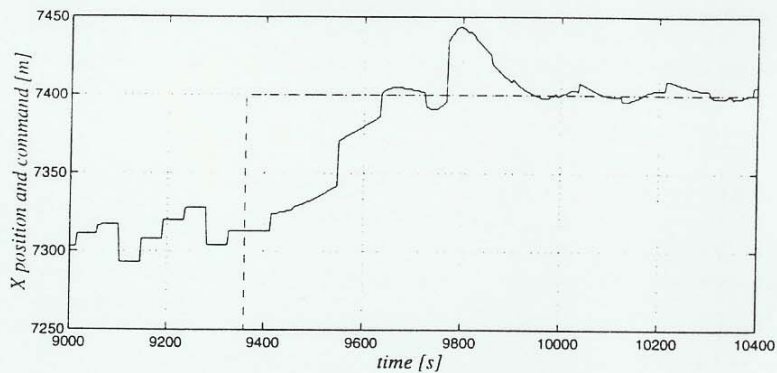


Fig18 Commanded and measured Y position

## 7- Conclusions

This paper presented the main results obtain with the free swimming vehicle SIRENE, equipped with on-board resident systems for navigation, guidance and control and operated through an acoustic bi-directional link proven up to 6000m and simulated up to 9000 m from the surface ship. A key component in the systems developed is the on-board autonomously supervised, integrated navigation that fuses dead reckoning and acoustic long baseline positioning data. The vehicle was tested at sea successfully and the new concept shows considerable promise for future subsea intervention.

In the scope of the MASTII project DESIBEL program the handling and management of benthic station was also tested at sea with success with the deep sea VICTOR ROV - build and operated by IFREMER - fitted with a high performance hydraulic telemanipulator for more complexes tasks.

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