Girona 500 AUV: From Survey to Intervention

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***Abstract*—This paper outlines the specifications and basic design approach taken on the development of the Girona 500, an autonomous underwater vehicle whose most remarkable characteristic is its capacity to reconfigure for different tasks. The capabilities of this new vehicle range from different forms of seafloor survey to inspection and intervention tasks.**

***Index Terms*—Autonomous underwater vehicle (AUV), intervention AUV, vehicle design.**

I. Introduction

In recent years, autonomous underwater vehicles (AUVs) have demonstrated their capabilities in many important applications in fields such as oceanographic research, offshore oil and gas industry, and military operations. However, their use is mostly limited to tasks related to the collection of sensor data and the generation of detailed maps of the seafloor. Some recent developments indicate a growing interest in expanding the AUVs capabilities with intervention skills [1]– [3]. The so-called intervention AUV, or I-AUV, is the result of incorporating one or more manipulators to the submersible with the objective of performing autonomous intervention tasks such as the collection of samples, maintenance works or salvage operations to name but a few. The main advantage of I-AUVs, as an alternative to the current remotely operated vehicles (ROVs), would be their lower operational cost, since they will not require the deployment from expensive oceanographic vessels with a heavy crane, automatic tether management system, and a dynamic position system.

This paper presents the Girona 500, a new AUV developed at the Underwater Robotics Laboratory of the University of Girona, Spain, that has been designed as a research platform with capacity to reconfigure for many different applications, ranging from the classical sonar and video imaging surveys to the challenging autonomous intervention tasks.

One of the main concerns during the design of the Girona 500 was developing a vehicle with compact dimensions but with a reserved payload volume large enough to accommodate different instruments, including bulky equipment such as a robotic manipulator. Many torpedo-shaped vehicles address this issue by means of a modular design [4], [5]. Cylindrical midsections, or modified nose and tail cones, can be incorporated into the basic vehicle configuration to enable new functionalities without any restrictions other than those imposed by the maximum allowed length of the vehicle. The main drawback of torpedo-shaped submersibles is that their distance between the center of gravity (CG) and the center of buoyancy (CB) is very small (generally, on the order of a few centimeters), which leads to a poor stability, making them less appropriate for intervention or imaging tasks.

Alternatively, other autonomous vehicles adopt ROV-like open frame configurations that make easier to fit additional accessories and also offer better stability than torpedo-shaped vehicles, although at the cost of a lower hydrodynamic performance [6], [7]. To the best of the authors knowledge, the I-AUVs that have been developed until now are very heavy platforms that fall into this second category [2], [3].

There are other less common design variants that do not fit in any of these two categories [8]. Among them, we want to remark a class of vehicles that are composed of multiple streamlined hulls held together by some type of light frame. This approach represents a compromise between the low drag hydrodynamics of torpedo-shaped vehicles and the simplicity and stability of open frame platforms. The most notable exponents of this design philosophy are the ABE [9] and the SeaBED [10] AUVs developed at the Woods Hole Oceanographic Institution.

The Girona 500 also falls in this last category. The versatility of a multihull configuration fits perfectly with the goal of a vehicle with survey and intervention capabilities. Moreover, to adapt the vehicle to the requirements of each particular mission, payload equipment can be installed on a reserved area that represents about 15% of the total vehicle volume. Although this free space has limited dimensions, it has been concentrated on a single volume that is large enough to host a small manipulator. Unlike other similar vehicles, the Girona 500 has also the capacity to modify its propulsion system to actuate the required degrees of freedom (DOFs) and to incorporate more flotation modules to adjust the buoyancy with each particular configuration.

The remainder of this paper is organized as follows. Section II presents the general characteristics of the vehicle and some details of the mechanical design. Section III describes the reconfigurable propulsion system. Section IV introduces the Girona 500 power electronics, while Sections V and VI are dedicated to the control electronics and the software architecture. Sections VII and VIII describe the basic sensor suite and some examples of mission-specific payloads currently under development. Section IX describes some preliminary results obtained during the vehicle testing. Finally, Section X concludes this paper.

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II. Mechanical Design

The vehicle, designed for a maximum operating depth of up to 500 m, is composed of an aluminum frame that supports three torpedo-shaped hulls of 0.3 m in diameter and 1.5 m in length as well as other elements like the thrusters. This design offers a good hydrodynamic performance and a large space for housing the equipment while maintaining a compact size that allows us to operate the vehicle from small boats. The overall dimensions of the vehicle are 1 m in height, 1 m in width, 1.5 m in length, and a weight of less than 200 kg.

The vehicle main frame is made of 6082-T6 aluminum alloy and is composed of two T-shaped pillars screwed to three U-shaped profiles that serve as backbone to each one of the three torpedo-shaped hulls. The U profiles not only serve as support to the different equipment but also work as ducts to convey the wet cables for power and communications. The same principle is applied at the top part of the T-shaped pillars, which also use a U profile to convey the cables into the interior of the hollow pillars, making possible the connection between the upper and the lower part of the vehicle. The same aluminum alloy is used in some small parts that work under stress like the supports for the batteries and the thrusters, while other parts made of acetal material subject less critical elements, such as the sensors. The three bodies that compose the vehicle are covered with a thermoformed ABS plastic skin whose streamlined shape is based on the Myring hull profile equations [11]. The skin provides protection to the sensible equipment and reduces the drag of the vehicle.

The flotation modules, made of an epoxy composite foam with a density of 400 kg/m^3, are placed on the top part of the vehicle. Their principal mission is to make the vehicle almost neutrally buoyant. In fact, the Girona 500 is slightly buoyant as a safety measure in front of a critical failure in the control system. The blocks are cylindrical and have a groove on their lower part that fits into the hull's U-shaped profiles, letting the wet cabling pass through them. Only a single stainless steel hose clamp is required to subject each block, making it very easy to move, add, or remove modules to adapt the buoyancy according to the needs of a particular payload configuration.

The vehicle electronics are contained inside two cylindrical pressure housings made of hard anodized 6082-T6 aluminum alloy. The first housing, which contains mainly the control electronics and is positively buoyant, is placed in the upper port-side hull, while the second one, which contains the battery cluster (the most heavy component of the vehicle) and some power electronics, is placed in the lower hull. The lower hull also accommodates the payload, which is placed on the front part and occupies almost half the available volume. This location is the most adequate for the majority of equipment that may be installed in the payload, particularly survey sensors, since it offers good forward and downward visibility.

As commented earlier, the positively buoyant elements, such as the flotation foam and the control electronics housing, are placed on the top part of the vehicle, while heavier elements such as the batteries and the payload are placed in the lower hull. This particular arrangement is not arbitrary, but designed to create a very stable platform in roll and pitch by increasing the vertical separation between the CB and the CG. This distance will depend on the vehicle configuration (equipped payload, flotation blocks, number of thrusters), but as can be seen in Fig. 3, this will be of about 10 cm for most of the situations. This passive stability in pitch and roll makes the Girona 500 particularly suitable for bathymetric and imaging surveys as well as for intervention operations.

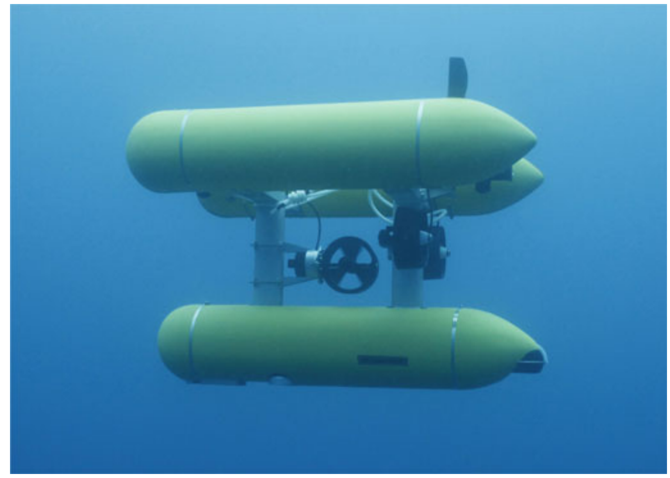

Fig. 1. Girona 500 AUV during its first trial at sea.

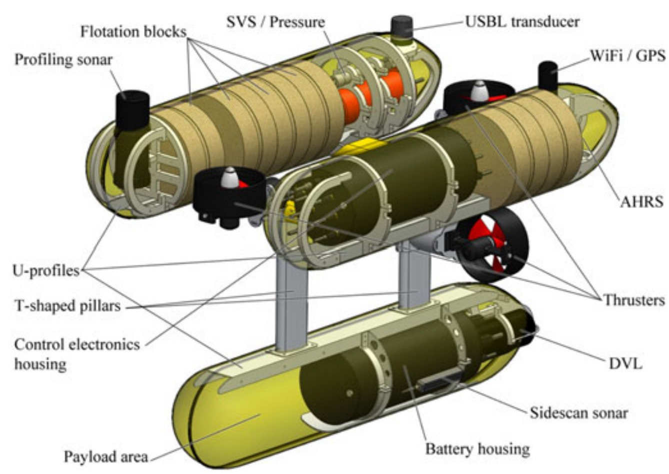

Fig. 2. Girona 500 AUV internals.

III. Propulsion System

To meet the requirements of the diverse applications envisioned for the Girona 500, its propulsion system has been designed to admit different thrust configurations ranging from the redundant vectored thrust typical of intervention ROVs to more lightweight and efficient arrangements preferred for long endurance survey tasks. This configurations can be easily implemented by means of reconfigurable mechanical parts and a junction box with the capacity to connect up to eight thrusters, providing regulated power and RS485 communications.

On its minimal setup, the Girona 500 is equipped with three thrusters, two to actuate the surge and yaw and one to actuate

Payload conf. #	Weight (kg)	Distance (cm)
1 (Empty)	141	8.6
2 (Multibeam sonar, camera, LED lights)	147	9.5
3 (RAUVI manipulator)	169	10.5

Payload conf #	CB	CG
1	■	□
2	●	○
3	▲	△

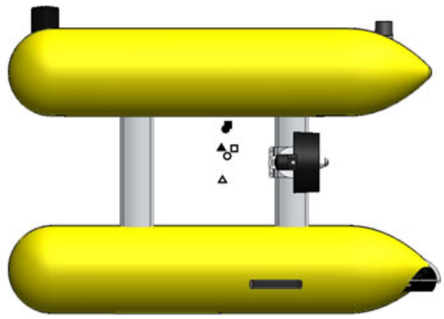

Fig. 3. Positions of the CB and CG for different payload configurations.

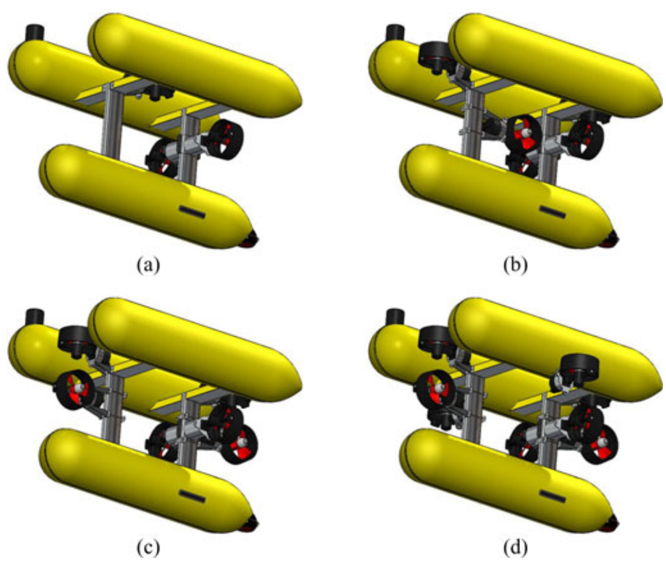

Fig. 4. Some thruster configurations for the Girona 500 propulsion system. (a) Three thrusters, 3 DOF. (b) Five thrusters, 5 DOF. (c) Six thrusters, 5 DOF. (d) Eight thrusters, 6 DOF.

the heave [see Fig. 4(a)]. Since the vehicle is not equipped with a rudder, two is the minimum number of thrusters required to control the horizontal motion of the vehicle. On the other hand, only one thruster is necessary to control the vertical motion because of the passive stability of the vehicle in the pitch and roll DOFs. This configuration, however, requires the alignment of the vertical thrust vector with the vehicle's gravity and buoyancy centers and, as a consequence, makes it necessary to carefully balance the vehicle (particularly, in the pitch DOF) each time a different payload is equipped. In the same way, the changes in the vertical position of the CG can be addressed by adjusting the height of the horizontal thrusters, whose supports can be mounted along the rear pillar.

The standard Girona 500 configuration is the four thruster setup shown in Fig. 2. The addition of another vertical thruster allows actuating the pitch DOF and provides redundancy on the heave movement, making possible to surface in case of failure of one of the thrusters. Moreover, in the event of a damaged thruster, the structural parts have been designed so they can be rearranged to switch between the four and the three-thruster configurations, rapidly enabling the vehicle back to operation. It is worth noting that the addition of a new thruster does not necessarily imply that the power consumption will increase. The power-to-force ratio behaves linearly for all the operating range, and therefore, the consumption of a single thruster is practically equivalent to the combined consumption of two thrusters producing half of the each thrust.

In the presence of currents, or when the task at hand demands the capacity of executing lateral movements, there is the possibility to mount bow and stern thrusters as shown in Fig. 4(c). As a result of this configuration, the vehicle gains control of the sway motion and redundancy in the horizontal plane. In a similar way to that previously introduced for the vertical thrusters in the three and four-thruster configurations, the lateral motion can also be achieved by installing a single thruster in the middle of the two pillars, although at the cost of losing the redundancy [see Fig. 4(b)].

Finally, two more vertical thrusters can be incorporated into actuate the roll DOF and hence, to achieve a fully actuated vehicle [see Fig. 4(d)]. Because of the passive stability of the vehicle, this configuration will be only employed in tasks, such as a free-floating manipulation, where a high lifting thrust or a precise control is required.

IV. Power System

The power source of the Girona 500 is a battery cluster composed of 24 small rechargeable Li-ion battery packs with a combined capacity of over 2.2 kW·h of energy. Each battery pack has a capacity of 95 W·h with an output of 14.4 V and is equipped with its own integrated safety circuit that monitors and reports different key parameters (temperature, voltage, current, and time to full charge/discharge). Three high current controllers, each with the capability to manage up to eight battery packs, are responsible of all the safety aspects required by the charge and discharge of the system. Another module enables multiple controllers to be clustered together and provides a single RS-232 interface to manage and monitor the state of the system at any time. The battery cluster can be completely charged in about 4 h using a fixed 20 V–50 A switching-mode ac–dc power supply.

As previously commented, the battery cluster is contained into a watertight housing placed on the lower body of the vehicle. The housing also stores three high-intensity dc–dc converters connected in parallel that power the propulsion system. The converters step the output from the battery cluster up to 48 V with a combined maximum power of 720 W. As a result, the power system contained in the housing can supply two different outputs. First, 14.4-V unregulated power obtained directly from the battery cluster, which is connected to the control and power management housing in the upper part of the vehicle, and second, a regulated power of 48 V, which is connected to the thruster junction box to supply power to the propulsion system. In addition, the housing also has two connectors to charge the batteries with the external power supply and also a serial RS232 communication with the upper housing to monitor and control the operation of the battery system.

The power management for the rest of the vehicle takes place in the upper housing. There, nine different dc–dc converters receive the unregulated 14.4 V from the batteries and provide regulated power for each one of the subsystems. First, a 50-W PC104 power supply outputs the multiple voltages required for the operation of the two embedded computers. Then, a dc–dc converter provides 12 V at 150 W for the LED lighting system. Finally, seven more low power small dc–dc converters (10 to 35 W) supply power to the rest of the devices, primarily sensors. The purpose of using many low power converters instead of one with a higher output is to provide a cleaner power supply to sensors that may be sensitive to fluctuations. Moreover, a relay circuit placed before each dc–dc converter makes possible to independently switch ON and OFF each one of the systems, allowing a more efficient power management during the execution of the mission.

The possibility of using interchangeable payloads has also been foreseen during the design of the power system. A cable connected to the upper housing brings two different power supplies to the payload area at the front of the lower body. The first one is a 24-V-regulated power at 10 W, which has been chosen as a very common operative voltage for many sonars and other underwater sensors, making their installation straightforward. The second one is the 14.4 V of unregulated power obtained directly from the battery cluster. This power source makes possible designing more complex payloads, with multiple sensors and even other elements like additional computers or lighting systems, up to a combined maximum power of 90 W. However, this comes at the cost of including the required dc–dc converters as part of the payload. In the same way, as the other subsystems, the payload power sources can also be independently controlled by means of two relay circuits.

During the design phase, the battery system was dimensioned to provide about 8 h of operation. However, the calculations were approximate and largely dependent on the different possible vehicle configurations. The better way to evaluate the real vehicle endurance is through experimental validation. The first preliminary results are described in Section IX.

V. Computer Architecture

In addition to the power management electronics commented in the previous section, the upper housing also contains the computer systems that are in charge of the vehicle control and the sensor data processing and logging. The vehicle's main computer is a PC-104 1.6 GHz Intel Atom processor system running Linux, which complemented with a serial communications expansion card, offers a total of 12 RS232/485 channels to interface with sensors and other subsystems such as the payload. An additional expansion board, a frame grabber, makes also possible to acquire images from the Girona 500 video system. This computer, which has been chosen because of its reduced dimensions and low power consumption, will be reserved for the execution of basic mission control and navigation tasks as well as for sensor data logging. On the other hand, a secondary PC-104 computer equipped with a 1.2 GHz Core2Duo processor will be available for other tasks requiring higher computational power such as image processing or the execution of mapping algorithms. Following the philosophy described in Section IV, this secondary computer can be turned ON and OFF according to the mission requirements with the objective of saving power. Obviously, the primary computer, which is in charge of managing all the other subsystems, will be always ON.

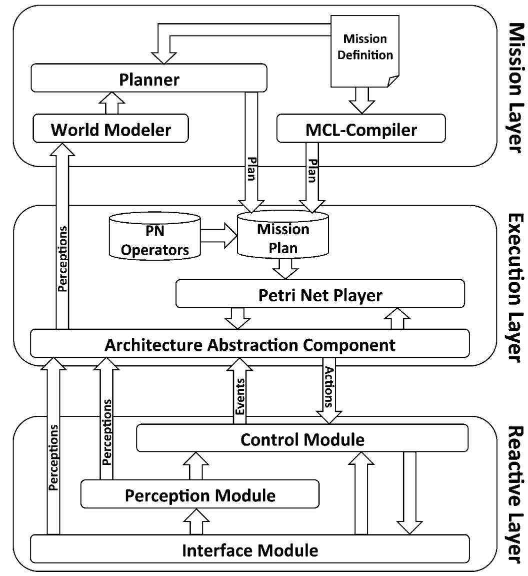

Fig. 5. Example of a three-layered component-based control architecture.

Both computers are networked through a eight-port 100 Mb/s Ethernet switch. The remaining Ethernet ports are employed to connect sensors that require a high data transfer and to interface with other systems that may be part of the payload. A WiFi access point with an amplified omnidirectional antenna is also connected to the network with the objective of providing medium range communications with a base station while on surface. Alternatively, the vehicle can also be interfaced via Ethernet using a tether.

VI. Control Architecture

The architecture implemented in the Girona 500 is called Component Oriented Layer-Based Architecture for Autonomy (COLA2). This architecture has its components organized in three different layers: the *mission*, *execution*, and *reactive* layers (see Fig. 5).

A. Reactive Layer

The reactive layer is dependent on the sensors and actuators being used. However, it has been divided into three modules to reduce such dependence: the *vehicle interface module*, the *perception module,* and the *guidance and control module*.

The vehicle interface module contains components, named *drivers*, which interact with the hardware by reading data from sensors and sending commands to the actuators. The drivers also convert all the data to coherent units and reference it to the vehicle's fixed body frame. Optionally, a Hardware In the Loop simulator called *Neptune* [12] can replace the drivers allowing the execution of the architecture in simulation mode without modifying the rest of the components.

The perception module receives the data gathered by the vehicle interface module. The elements that compose this module are known as processing units. They are the navigator, the obstacle detector, and several target detectors. The navigator processing unit estimates the vehicle position and velocity merging the data obtained from the navigation sensors by means of a Kalman filter [13]. The obstacle detector takes advantage form onboard acoustic sensors to determine the distance to potential obstacles. On the other hand, target detectors can process acoustic or visual data to extract features that may be relevant for certain applications such as object detection or cable tracking [14].

Finally, the guidance and control module includes a set of behaviors, the coordinator, and the velocity controller. The behaviors are basic robot functionalities that can range from a component that checks the battery level [e.g., *batteryMonitor(enable)*] to a component that navigate toward a 3-D way point [e.g. *goto(x, y, z)*]. In general, behaviors have a goal to be achieved, for instance, the goal of *achieveAltitude* would be to drive the robot at a constant altitude. These behaviors, receive data from the vehicle interface and perception modules, making them independent from the physical sensors and actuators installed on the vehicle. Then, a coordinator combines all the responses generated by the different enabled behaviors into a single one [15] while the velocity controller turns this response into a force vector for each thruster driver to control the vehicle's velocity. A simple proportional integral derivative controller is used for this task.

B. Execution Layer

The execution layer acts as the interface between the reactive layer and the mission layer. It translates high-level plans into low-level commands enabling and disabling behaviors in the reactive layer. The execution layer is composed of two main components: the architecture abstraction component (AAC) and the Petri net player (PNP). The AAC is located at the bottom of the execution layer and keeps the mission and execution layers vehicle independent, leaving the reactive layer as the only element dependent on the vehicle's hardware. The AAC offers an interface toward the reactive layer based on three types of signals: *actions*, *events,* and *perceptions*. Actions enable or disable basic behaviors. Events are triggered in the reactive layer to notify changes in the state of its behaviors. Finally, perceptions, meaning specific sensor or processing unit values, are transmitted from the reactive layer to the mission layer to extract relevant information about the current world state when an on-board planner is used.

The second component, the PNP, executes the mission plan given by the mission layer. The plan is defined by means of Petri nets that describe which actions have to be sent depending on the received events. Basically, it acts as a discrete event system (DES) connecting discrete plans with continuous behaviors. Petri nets are a popular formalism to encode predefined missions for AUVs [16], [17]. A more detailed description of their use in the proposed architecture is presented in [18].

C. Mission Layer

Nowadays, predefined plans are the state of the art for AUV missions. However, offline plans may fail during execution when assumptions upon which they were based are violated [19]. On the other hand, the use of online generated plans may result in unpredictable vehicle behaviors. Therefore, it is worth to find a compromise between predefined offline plans and automatically generated online plans. The COLA2 architecture introduces a high-level language, named Mission Control Language (MCL), for easily describing offline plans that are then automatically compiled into a formal Petri net [20]. Additionally, the inclusion of an onboard planner capable of automatically sequence *planning operators* previously described using the same MCL has been studied [21]. Therefore, a mission can be either predefined by a user by means of a high-level language, the MCL, or using this same language, predefine some planning operators and let an onboard planner to automatically execute, at each moment, the ones which are most appropriate to fulfill the mission.

Despite being a standard layered architecture, the novelty of the COLA2 architecture resides in the combination of components in each layer. First of all, the reactive layer can be seen as a behavior-based architecture in which a set of behaviors are coordinated to fulfill a goal. However, instead of using the subsumption approach [22] to coordinate them, the execution layer is the one in charge of enabling, prioritizing, and configuring behaviors following the plans described in the mission layer. This approach offers a good response without being limited to simple missions, as occurs in pure behavior-based architectures. Other advantages of the COLA2 architecture are the inclusion of an AAC, which makes the execution and mission layers independent from hardware changes, and the use of a formal DES (Petri nets), which allows us to systematically verify and execute mission plans without complicating their description thanks to the MCL. Finally, onboard deliberation capabilities are also available by means of a simple planner.

VII. Sensors

In addition to mission-specific sensor systems that may be installed as part of the payload, the Girona 500 is also permanently equipped with common survey and navigation sensors. The traditional dead-reckoning navigation is accomplished by means of a 614.4-kHz phased array Doppler Velocity Log (DVL) and a solid state Attitude and Heading Reference System (AHRS) aided by a single axis Fiber Optic Gyro (FOG) for a better heading stability and precision. On the other hand, absolute position fixes can be obtained by means of a GPS when the vehicle is on the surface and using an Ultra Short Baseline (USBL) while underwater. The high-accuracy USBL system, which operates in a frequency band from 31 to 43.2 kHz, also comprises an acoustic modem that makes possible not only to localize the vehicle but also to establish communication between the vehicle and the surface unit. Since they share the same electronics and transducers, the total size, weight, and power consumption is reduced. It is worth mentioning that for safety purposes the USBL transponder mounted in the Girona 500 is equipped with its own batteries, making possible to localize the vehicle in the event of a complete electrical failure.

The perception of possible obstacles around the vehicle is accomplished by means of a dual frequency (0.6 and 1.1 MHz) profiling sonar installed on the top of the vehicle. The mechanically scanned sonar head provides a complete 360° view of the vehicle surroundings up to a maximum range of 80 m. In most situations, the range measurements provided by the DVL are sufficient to determine the altitude of the vehicle over the seafloor. However, in the presence of a rough terrain or in those situations where it is necessary to navigate very close to the bottom, the profiling sonar can be mounted horizontally with the objective of scanning the seabed along the vehicle path for incoming obstacles.

With the objective of improving the data accuracy of all the acoustic devices, a sound velocity sensor (SVS) has been included to create speed of sound profiles. In contrast to the classical conductivity/temperature/depth approach, the SVS determines the speed of sound by using a single pulse of sound traveling over a known distance. This direct measurements provide higher accuracy and an almost instantaneous response without requiring any calibration. Despite the small dimensions of the SVS, it also includes as an option a high-accuracy pressure gauge for measuring the vehicle depth.

The basic survey equipment of the Girona 500 is composed of a sidescan sonar and a video system. The sidescan sonar can be operated at three different frequencies, 260, 330, and 800 kHz, with a maximum range of up to 100 m and a resolution of 1000 data points per side. The video system is comprised of a color CCD video camera complemented with a pair of 40-W LED lights.

VIII. Application-Specific Payload

In addition to the basic sensor suite presented in the previous section, the Girona 500 has a reserved large cylindrical volume (approximately Ø0.3 × L0.6 m), situated on the front part of the lower body, for mission-specific payload equipment. The payload instruments can be mechanically interfaced with the vehicle structure by means of the lower hull's U-shaped aluminum backbone and connected to the power and control electronics housing in the upper part of the vehicle by two wet cables (power and communications) ducted through the front pillar of the vehicle. The communications cable provides one Ethernet and two serial RS-232 connections with the vehicle's computer systems, while the power cable provides 24 V of regulated power at 10 W and 14.4 V of unregulated battery power.

The first payload system for the Girona 500 (see Fig. 6) has been developed in collaboration with the Universitat Jaume I and the Universitat de les Illes Balears in the context of the Reconfigurable AUV for Intervention missions (RAUVI) Spanish project. It is composed of a light duty 4 DOF electrical manipulator, a video system, and their corresponding control electronics [23]. The main goal of the project is to perform a two-step autonomous underwater intervention mission consisting of an initial video survey phase in which a particular object (a flight data recorder, also known as black box) is localized, followed by an intervention task in which a hook attached to the robotic arm is used to retrieve the black box.

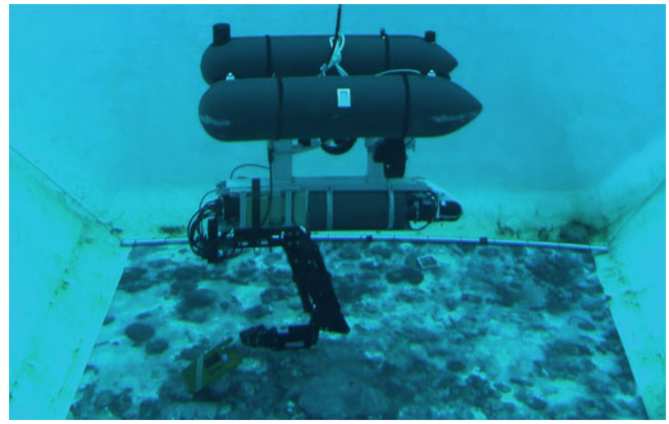

Fig. 6. Girona 500 AUV during an intervention at the CIRS water tank.

A second payload for intervention is being developed as part of the TRIDENT FP7 project. The main difference with the previous payload is the higher dexterity of the system to be achieved with a 7 DOF manipulator and a three-fingered hand. The project will expand the capabilities demonstrated in the RAUVI project with the inclusion of an autonomous surface craft (ASC) that must operate cooperatively with the I-AUV during the survey phase to generate geo-referenced visual/sonar maps of the area. In a second phase, after selecting the target of the intervention from the resulting map, the I-AUV (assisted by the ASC) will navigate to the geo-referenced position to perform the defined manipulation task.

The third payload to be developed is part of another Spanish project under the title "Multi-modal 3-D Mapping for the Characterization of the Seafloor using an Autonomous Robot" that proposes the development of a new high-resolution optical seafloor mapping system for large areas of the ocean floor, with direct applications to environmental studies, oceanography, geology, biology, and the offshore industry. The payload will include a stereo pair composed of two high-resolution digital cameras, an altimeter, and the required electronics for the storage and manipulation of the image sequences.

IX. Results

The Girona 500 is currently at the final stages of development and has initiated the in-water testing phase in which the vehicle will be incrementally tested for longer mission times and larger depths. The first trials performed at the water tank of the Research Center In Underwater Robotics (CIRS) at the Universitat de Girona have already demonstrated the capacity of the system by successfully executing the two scenarios envisioned in the RAUVI project [23]. For the tests, a digital image of a real seafloor printed in a 3.5 × 7 m poster was placed at the bottom of the water tank together with a mock-up black box situated in an unknown position (see Fig. 6).

In the first phase, the Girona 500 was programmed to autonomously survey the bottom following a grid-shaped

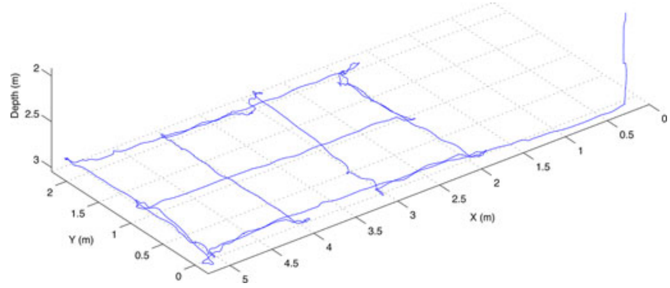

Fig. 7. The survey trajectory executed by the Girona 500 AUV.

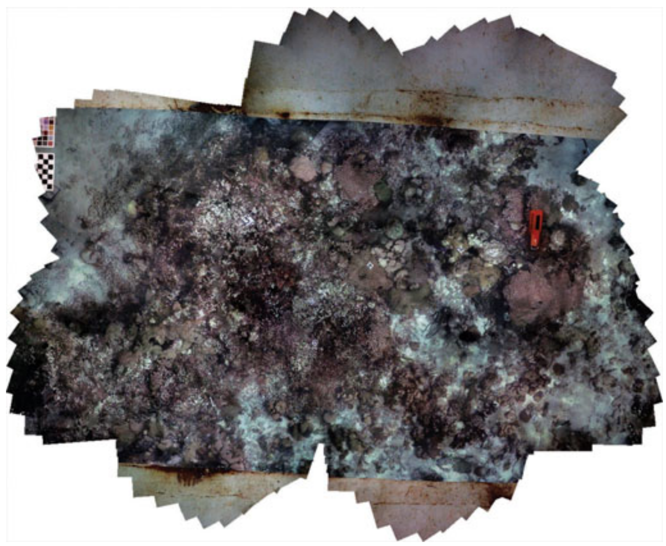

Fig. 8. Image mosaic from the images acquired during the survey mission.

trajectory with 1 m distance between parallels swaths. The resulting trajectory estimated by the navigation system can be observed in Fig. 7. Then, the images captured with the down-looking video camera were used together with the navigation data to generate a photomosaic [24] of the surveyed area with the objective of determining the position of the black box in the scenario (see Fig. 8).

During the second phase, the vehicle navigated autonomously to the coordinates where the black box should be placed according to the image mosaic. Then, with the black box on the vision system's field of view, the vehicle initiated a station keeping behavior to keep the position and altitude with respect to the target. Finally, the manipulator executed the autonomous hooking task and retrieved the black box (see Fig. 6). The experiment was successfully executed several times, demonstrating the reliability of the proposed system.

The survey capacities of the vehicle have also been tested in the field (see Fig. 1). The first sea trials took place near Roses, in the north of the Catalan coast (Spain), and consisted in the execution of several autonomous missions. The missions demonstrated the capacity of the vehicle to navigate to a given geographic coordinates, with the help of the onboard GPS, to then initiate the immersion and perform a survey trajectory at a controlled depth. The execution of the missions was monitored from a surface boat by means of the USBL system. Fig. 9

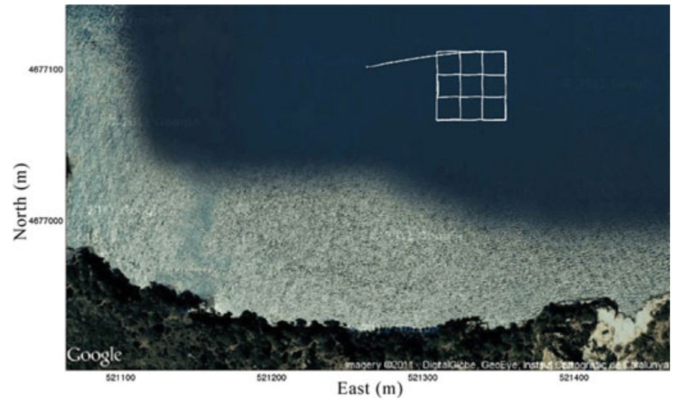

Fig. 9. Trajectory executed during field trials near Roses (Spain).

shows the navigation data for a mission where the vehicle was commanded to perform a grid-shaped survey trajectory of an area of 45 $\times$ 45 m with 15 m between transects and at 20 m depth. The mission took 26 min to complete with the vehicle moving at a velocity of 0.6 knots.

The field trials also gave a more clear picture of the battery system's real endurance. During the experiments, the vehicle was operative for a total period of 6 h, consuming 45% of the available energy. However, only 87 min can be accounted as real mission time, which required 25% energy. The rest of the time the vehicle was in stand-by, waiting for the missions to be prepared, doing tests or retrieving data. According to that, one can expect the Girona 500, with a 5-thruster configuration and all the sensors on, to execute missions of about 6 h before depletion. It is reasonable to expect that the vehicle, in a four-thruster configuration and with a smarter power management, will get closer to the 8-h endurance time targeted during the design phase.

X. Conclusion

We have presented the Girona 500, a compact, lightweight AUV with survey and intervention capabilities. The main characteristic of the vehicle is that it can be adapted for different tasks by equipping mission-specific payloads, reconfiguring the propulsion system, and adjusting the vehicle buoyancy. The principal design aspects have been described, as well as the different subsystems and software architecture. Finally, several examples of payload systems have been presented together with preliminary experimental results.

Future work will include extensive testing of the new platform during forthcoming sea trials as well as the development of new payload systems.

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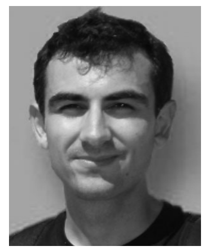

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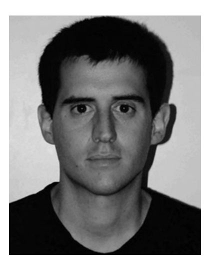

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