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Operational and scientific capabilities of Ariane, Ifremer's hybrid ROV

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Abstract :

Latest underwater system in the French Oceanographic Fleet, Ariane is a hybrid ROV designed to meet new needs in terms of exploration and intervention in coastal areas, up to 2500m depth. Launched in 2010, the development of this new system was strongly motivated by changes in environmental policies. The rise of Protected Marine Areas and the establishment of European directives such as the Marine Strategy Framework Directive in 2008 have led to the emergence of new scientific programs for the analysis and the monitoring of underwater ecosystems. Based on an innovative hybrid concept, Ariane is designed to be operated from a wide range of light vessels without dynamic positioning capabilities as a key enabler to respond to the scientific community's requirements and comply with stringent budgetary constraints. After 6 years of development and technical sea trials, Ariane was commissioned in the beginning of 2017 for an opening cycle of scientific cruises. By the end of 2018, the system had totaled 130 dives that cover a representative panel of operations and highlight a number of innovating features.

Keywords : underwater vehicle, vehicle architecture, vehicle deployment, hybrid system, scientific exploration

I. INTRODUCTION

In 2010 the French national oceanographic institute IFREMER launched a development program aimed at the design and implementation of a new underwater vehicle, called *Ariane*, to respond to new challenges in oceanographic science. The program stems from the requirements of the scientific community to explore and perform intervention tasks in coastal areas and in natural environments whose morphology represents an impediment to existing tools. Such environments include cold-water coral reefs, underwater canyons, seamounts, ridges rift valley walls and continental margins, where the predominantly rocky substrate favor the development of rich faunal settlements. These crucial yet extremely fragile ecosystems are exposed to ever growing threats represented by human activity. A number of international directives have been issued in order to enforce the requirement to map and monitor their evolution, such as the European Marine Strategy Framework Directive marine environmental policy established in 2008 [1]. The emergence of new environmental programs implies the increase of underwater operations needed, and particularly in coastal areas. In this context, use of non-DP type vessels and particularly coastal vessels, has been identified as a key feature for operational cost mitigation. The deep-sea underwater intervention systems of the French Oceanographic Fleet such as the manned submersible *Nautile* and the scientific work-class ROV *Victor6000*, require blue water research vessels. The hybrid ROV *Ariane* is based on an innovative and patented concept [2] that allows deployment from a wide range of light vessel without dynamic positioning capabilities, notably the coastal vessels of the fleet. This in turns allows *Ariane* to respond to the scientific community's requirements and comply with stringent budgetary constraints. It also offers better flexibility in the scheduling of offshore operations.

Fig.1. *Ariane* deployment from the oceanographic vessel *L'Europe* during Videocor cruise in 2017 (© Ifremer, O. Dugornay)

The validation at sea begun in late 2014 and lasted 2 years due to a 1 year set-back after a battery incident related to a Lithium-Ion thermal runaway. Preliminary technical trials [4] preceded the full operational commissioning in the beginning of 2017, for an opening cycle of scientific cruises. To date Ariane counts 130 dives that covered a representative panel of operations. Most operations were dedicated to exploration and ecosystem studies notably in canyon heads and on off-shore banks. Maintenance tasks were also planned on underwater observatories. Occasionally, *Ariane* was used for specific operations such as wreck search or inspection. This paper presents the innovative features and capabilities of Ariane considering feedbacks of the first scientific and operational results.

II. Innovative Hybrid ROV Concept

A hybrid ROV is a new generation of remotely-operated underwater vehicle that integrates an on-board energy source. Unlike conventional ROVs that require a power to be supplied from the surface through the umbilical, the link between hybrid ROV and vessel is limited to an optical fiber. In the past, other underwater vehicles have explored a similar approach, including fiber optic tethered AUVs [6], the pioneering HROV *Nereus* [7] and the *Swimmer* AUV/ROV [8] developed by IFREMER in cooperation with other European partners.

Today, existing hybrid ROVs such as *Nereid* [9] are based on a non-reusable fiber optic. The vehicle contains an optical fiber dispenser that unwinds the tether and allows long range operation up to 20 km. At the end of the dive, the link is cut and the recovery is managed in untethered autonomous mode (AUV mode). This concept enables operation in harsh environments such as under-ice exploration [8]; each subsequent dive requires the replacement of the optical fiber.

Ariane differs in that it integrates a reusable optical fiber and employs a dynamically controlled handling of its length. An on-board tether management system (TMS) has been developed to wind and unwind the optical fiber in order to maintain a constant load, regardless of vessel or vehicle motions. Based on a patented concept [2], the overall system integrates a load bearing optical cable (Fig.2. a) deployed from the support vessel, a static depressor weight (Fig.2. b), a two-part modular tether (Fig.2. c,d,e,f) and the vehicle itself.

The design of the modular tether is a key component. A short, flexible load bearing tether (Fig.2.c) stems from the depressor weight and connects to the buoyant vehicle plug (2.e). Connected to this float, 400m of light tether (Fig.2.f) are deployed by the TMS. A 4daN weight (Fig.2.d) is also added in order to produce the desired arch in the cable which allows to decouple and damp the heave dynamics of the depressor weight (Fig.2.a) and vehicle plug (Fig.2.e). The vehicle onboard TMS integrates a docking mechanism designed to clamp onto the plug (Fig.2.c) hence securely connecting the vehicle to the load bearing section of the cable. The light tether (Fig.2.f) is deployed from the vehicle's onboard TMS when undocked from the plug.

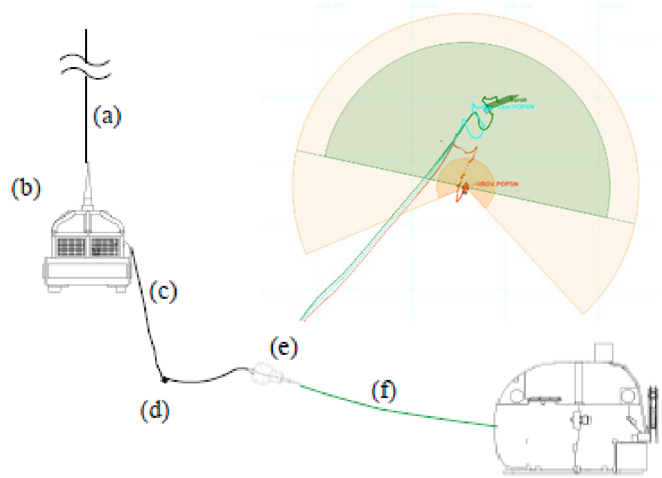

Fig.2. Elements composing the modular tether connection

Operational deployment involves connection of the vehicle to the short tether for towing it to operating depth, distant locations or simply back to the surface (Fig.3). The design allows to optimize power consumption and to secure the vehicle in launch and recovery phases and in critical situations during a dive. The surfacing phase concluding the dive in tethered mode requires no energy from the vehicle as the whole system is winched up as the vessel advances (Fig.3.b). When the operational depth is reached, the vehicle undocks from the plug and unwinds the light tether (Fig.3.c).

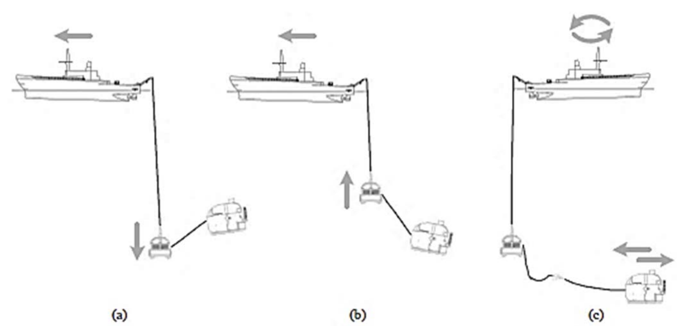

Fig.3. Operational deployment mode: (a) vehicle dive; (b) vehicle surface; (c) tethered operation

During operation and once the light tether deployed, the non-DP vessel tracks the trajectory of the vehicle with a significant degree of tolerance: the vessel needs to be positioned within only 300m from the depressor's vertical, maximal distance allowed by the light tether. It is the role of the vehicle's onboard TMS to regulate the length and tension of the light tether in order to prevent entanglement, propeller ingestion or to exceed the rupture load. The light tether consists of 450m of a 2.6mm reinforced optical fiber, with a breaking load exceeding 100daN. The TMS actively rewinds the fiber with a motorized spool and passively pays it out, in order to maintain the fiber tension (the feedback measure) to a safe value of few daN, depending on type of work (exploration, survey, station mode…) [4].

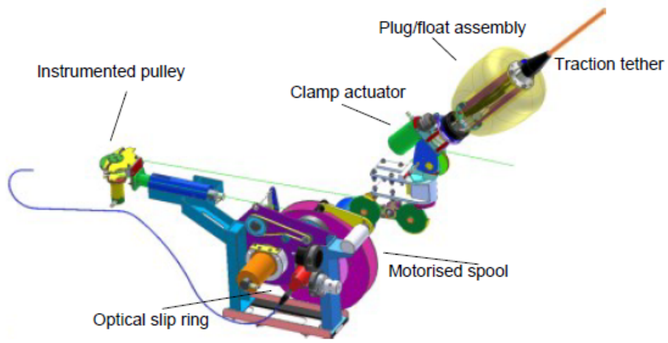

Fig.4. HROV *Ariane*'s Tether Management System

During diving, the ship is steered using a specifically developed tracking and guidance system integrated to IFREMER's own mission management software MIMOSA to evaluate and anticipate course corrections and following maneuvers to maintain the designed configuration (Fig.2). With this innovative concept, non DP light vessels can act surface deployment platforms. Today, *Ariane* is deployed from a number of coastal vessels managed by the French Oceanographic Fleet such as *L'Europe* (length: 30m), *Côtes de la Manche* (25m) and *Antea* (35 m).

The optical fiber is a fragile link and rupture may occur for several reasons. The most common is tether snagging on obstacles and typically on fishing lines. The risk is even greater when vessel and vehicle motions imply tether deployment in unexplored areas. In the worst case, the loss of communication is compounded by an anchorage of the vehicle. Failure of the tethered mode drives the hybrid ROV to an autonomous safety mode. The onboard control software's *Fault Response Manager* issues a number of safety procedures. Typically it can actuate a pyrotechnic fiber cutter to release the vehicle of its tether. Furthermore, an acoustic link between vehicle and depressor, implemented by a pair of Evologics S2C 18-34 kHz modems, restores communication allowing operators to keep the control of safety procedures. This autonomous mode might also be used to perform a fully autonomous mission of survey. So far, this functionality has not been used for scientific operations. The tethered mode offers a sensor feedback valuable even for survey operations and the vehicle real time control allows diving in harsh and complex environment such as canyons, key point of interest for *Ariane*.

III. VEHICLE FEATURES

The HROV *Ariane* integrates numerous innovative features designed to allow operation over complex and challenging terrains. The vehicle is depth-rated to 2500m and weighs in at a total of 1.8 tons, disposes of 19.6kWh of electrical energy provided by Li-Ion batteries that are conditioned in atmospheric pressure housings. Vehicle navigation is based on an optical fiber INS coupled with twin DVLs (Doppler Velocity Log) positioned to provide a velocity solution in varying degrees of terrain slopes. External absolute position sensors include surface GPS and low frequency USBL pinger.

The propulsion architecture chosen for the vehicle aims to optimize the use of electrical energy. The vehicle employs two main thrusters tilting around the horizontal axis and four fixed auxiliary thrusters to control 4 degrees of freedom. This configuration allows to implement several actuation schemes for ascend/descend phases and to adapt to the terrain profile or task requirements.

Furthermore, an 18 liter reversible ballast enables precise weight adjustment to optimize power thruster consumption. Tethered operation allows full feedback from the vehicle onboard systems to the control room, including two HD video cameras further four SD video cameras and a digital SLR still photo camera. A gigabit Ethernet link provides ample margin of interaction with the vehicle embedded controller, forward looking multibeam sonar data, navigation and payload sensors.

A. *VEHICLE DESIGN*

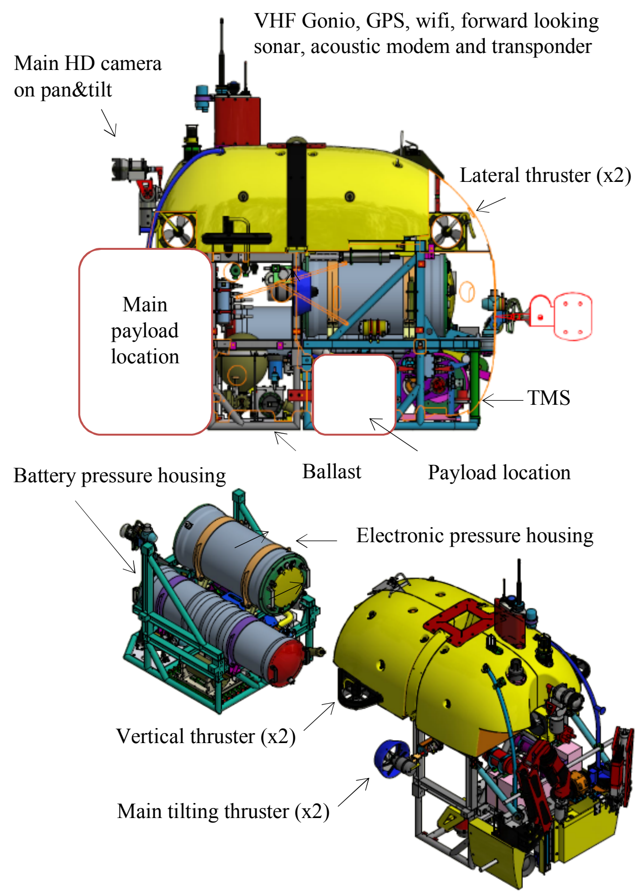

Fig. 5 : *Ariane* design

The operation from coastal vessels is a key feature for operational cost mitigation. Beyond the ability to operate from a non-DP type vessel, the system must be extremely compact to comply with limited deck space. The energy balance of combines overall compactness with the possibility to perform operational maintenance at sea. The vehicle's frame is composed of two parts (Fig. 5), which can be separated to facilitate access to the payload subsystems, actuators, sensors and to the two main pressure housings that integrate Li-Ion batteries and the main electronic systems, including on board controllers, converters, fiber-optic multiplexer, etc.

The forward section integrates an HD video camera mounted on a pan&tilt unit, associated led lighting and payloads, typically manipulator arms, digital still camera and a tool bay for intervention tasks. The vehicle is designed to integrate and carry up to 200 kg payload equipment (120daN in seawater) that is mainly located in the forward section of the vehicle. The different payload configurations available to date are detailed in a dedicated paragraph.

B. *ENERGY*

Ariane is powered by rechargeable Li-Ion batteries. The main 13.6 kWh 150Vdc battery is integrated in a dedicated pressure housing and powers thrusters and lighting. Additional batteries providing an additional 6 kWh are integrated in the electronic housing and power all electronics and payloads and offer power redundancy as a safety feature. The on-board energy capacity has been sized to match the requirements when operated from coastal vessels. The feedback of the first sea typical diving scenarios shows that in shallow water the autonomy on the sea floor is up to 6 hours (8 hours deck-to-deck), but for a 2500m depth operation with high consumption maneuvering the sea-floor autonomy can be limited to 4 hours. This level of autonomy is compatible with daily operation schemes on coastal vessels with reduced operational team.

A future increase of on-board energy is pre-designed with swapping to pressure tolerant Li-Ion batteries, increasing the total capacity to 26kWh, instead of the current 20kWh [5]. An upgrade along this path is considered to be implemented in the first five-year overhaul.

C. *PROPULSION SYSTEM*

From the outset of the project, the optimization of propulsion thrust and power efficiency has been a key objective. Other major requirements include the control in 4 degrees of freedom for station keeping and hovering manoeuvers. The design is based on a high metacentric distance to improve intrinsic stability during fine manipulation tasks.

The propulsion architecture features two main longitudinal thrusters that can be tilted ±90° with respect to the horizontal. The thrusters are positioned near the geometric center of the vehicle, resulting in near zero pitch attitude maintained throughout operation. Each thruster provides 55 daN of thrust and draws 2.7 kW from the main battery. The longitudinal thrusters are mounted onto a common shaft that passes through the vehicle body and can be tilted by a position controlled angular actuator. During bollard thrust tests the thruster provided approximately 60 daN of thrust at 3kW power. Four smaller thrusters, providing 19 daN each, are mounted in matching pairs to control the heave, sway and yaw dynamics.

The thrust scheme is modified in real time to suit the performed task: at low velocity and while station keeping the longitudinal thrusters are maintained at steady horizontal orientation (0°). Each controllable degree of freedom is actuated by an individual pair of thrusters; yaw dynamics are controlled through differential thrust of either the longitudinal or transversal thrusters. In survey or cruise mode, where longitudinal velocity reaches up to 2 knots, only the longitudinal thrusters and the tilting unit are used to control the vehicle. Actuation surge and heave dynamics is achieved through tilting of the main thrusters allowing the vehicle to navigate at constant velocity and distance from the terrain. This solution aims at improving propulsion efficiency by optimizing the direction of thrust as well as minimizing the number of actuators in use. Yaw is controlled through differential thrust on the longitudinal thrusts when their tilt angle is not greater than 20°, through the transverse thrusters otherwise.

In addition to thruster control, a mechanized Variable Ballast System (VBS) is used to enhance maneuvering accuracy. The VBS enables to adjust vehicle buoyancy up to 18 daN. It consists of a 20 liter pressure resistant sphere that can be filled with sea water via a solenoid valve. A hydraulic pump coupled with a pressure multiplier is used for emptying the tank. Water level in the tank is estimated at all times measuring the pressure of residual gas the sphere. Buoyancy adjustment is performed at the beginning of each dive and after sampling tasks, without any ballast jettisoning (no waste on seafloor).

D. *NAVIGATION*

Positional accuracy is key to the mission scenarios of *Ariane*. For this reason the vehicle is equipped with an extensive suite of sensors including a fiber optic INS, a depth transducer, a conductivity, temperature and depth sensor (CTD) and an innovative arrangement featuring two Teledyne RDI Explorer 600 kHz DVLs (Fig.6). In order to maintain positional accuracy while navigating over steep terrain and close to canyon walls, the forward looking and bottom looking DVLs are used simultaneously. Their acoustic pinging sequences are electronically synchronized to avoid interference. DVL raw measurements are processed in beam coordinates and used to provide a velocity estimate in vehicle reference frame. According to the terrain's slope, velocity aiding for the INS comes either from the down-looking or the forward-looking DVL or else from a third, virtual DVL obtained by combining the valid beams of both transducers [10].

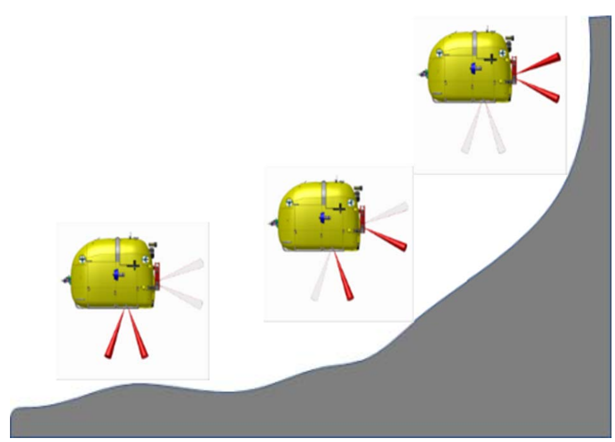

Fig.6. Double DVL arrangement in down looking and forward looking configuration.

Further navigation and positioning sensors used on the system include a DVL on the depressor weight providing depth and attitude measurements, and the ship mounted long range acoustic ultra-short base line (USBL) positioning system.

IV. SCIENTIFIC CONFIGURATIONS

To date, two main payload configurations have been developed. The first is labeled “exploration and sampling” and includes manipulator arms, sampling tools and scientific cameras. Most of the dives use this versatile configuration which caters to the needs of a wide range of scientific applications that focusing on studying marine ecosystems. The second configuration, named “mapping”, includes a multibeam echosounder which enables a high resolution acoustic bathymetry mapping thanks to the ability to perform close terrain following navigation. It allows combining acoustic survey with visual inspection and photogrammetry. This “mapping” configuration is typically used for preliminary inspection targeting identification of sites of interest for later exploration and sampling dives.

A. EXPLORATION AND SAMPLING CONFIGURATION

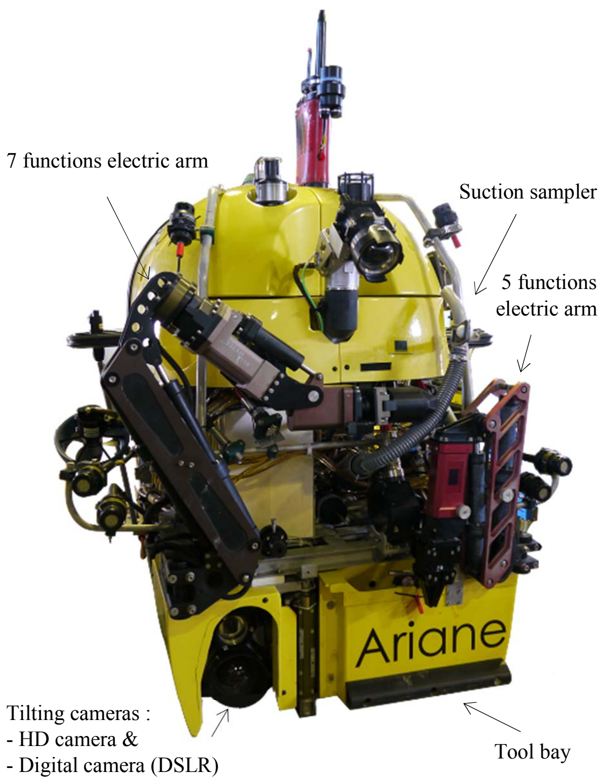

Fig. 7 : *Ariane* in “exploration and sampling” configuration

The robotic manipulation payload allows to perform precise underwater intervention tasks. Typical examples include core sampling, collection of biological or mineral specimens from the seabed and intervention on man-made structures. These tasks generally involve interactions with dedicated tools whose weight may range from a few grams to several kilograms in air and in water. This payload includes two electrical manipulator arms developed jointly by Ifremer and ECA Group. The dexterous arm is a 7-functions arm (type: ARM 7E MINI), designed to be able to perform complex intervention tasks where a precise positioning of the robot’s end effector is crucial. The second is a 5-functions arm (type: ARM 5E), intended to support the main intervention task; via tool grasping and vehicle docking. Both manipulator arms are controlled via software and power driver modules developed by Ifremer. Software control functions include cartesian and automatic trajectory control to enable complex and dexterous operations and optimize the time dedicated to *in situ* tasks. This “exploration and sampling” configuration integrates also a suction sampler with 6 bowls of 2.5 liters as well as a motorized tool bay (volume 100 l) for the transportation of sampling devices such as sediment corers or boxes (Fig. 8).

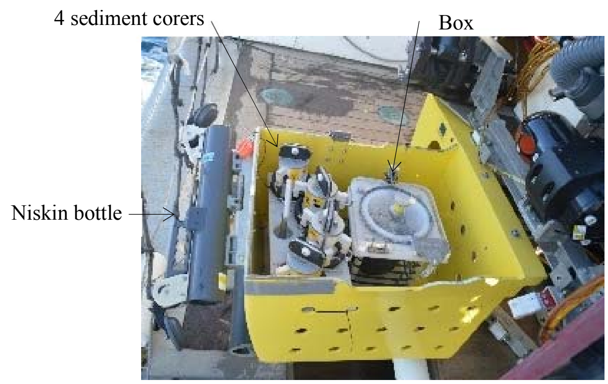

Fig. 8 : Illustration of the tool bay prepared for a dive (CANHROV cruise, 2016)

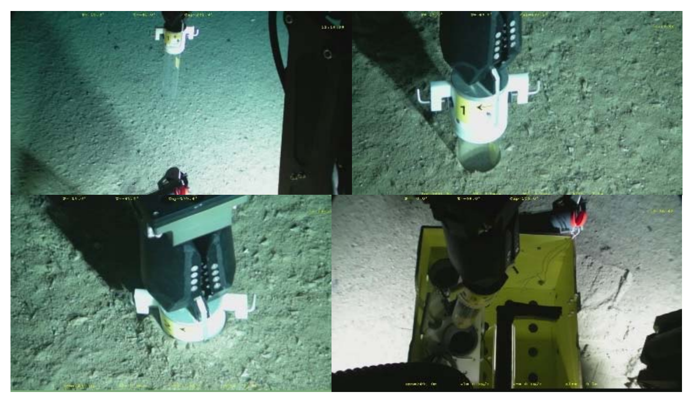

Fig. 9 : sampling task with a sediment corer (CANHROV Cruise, 2016).

In addition to the above listed sampling tools, this configuration integrates a set of cameras fitted to a tilt actuator comprising a HD zoom camera and a digital single-lens reflex camera (Nikon D5500) integrated in a pressure resistant housing with a combination of corrective lenses that allow high definition underwater imaging. Still images can be assembled into geo-referenced 2-dimensional (2D) or 3-dimensional (3D) mosaics, with the Ifremer’s software processing tool called Matisse [11]. The 2D mapping technique aims to merge many thousands of footprint images, into a single geo-referenced mosaic that results from images and navigation fusion. The 3D mapping technique is suited to areas of strong topographic interest. Reconstruction of real-scale 3D models is accomplished by structure-from-motion techniques using series of overlapping photos or snapshots of videos [11]. The ability to tilt the camera allows mosaicking vertical cliffs and any complex structure having both horizontal and vertical surfaces (Fig. 10).

Photogrammetry provides a permanent record of the scene, gives access to quantitative parameters, replicate measurements and by repetitive acquisition allows monitoring over time. This methodology has recently been used for monitoring marine habitats in a deep Marine Protected Area [12]. Using photogrammetry we are able to obtain knowledge on complex sites in canyons, and to reveal the size structure of populations of i.e. cold-water corals, as well as quantify the surface occupied by species (Fig. 11).

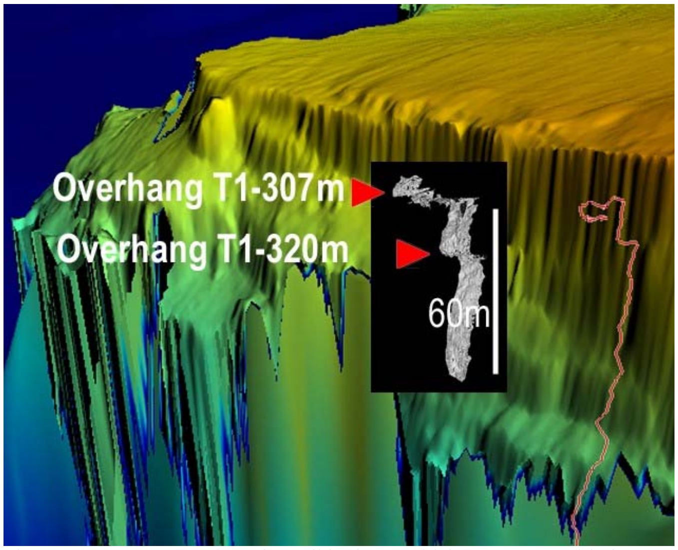

Fig. 10 : 3D-Representation of a wall in the Cassidaigne canyon, with the navigation track in red and the 3D model of two overhangs located at different depths [12].

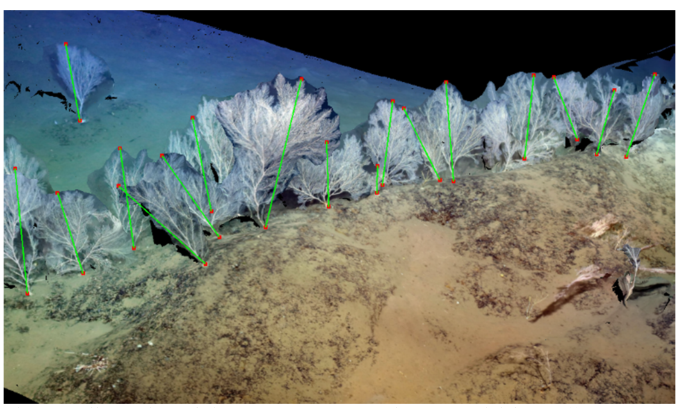
Fig. 11 : Illustration of size measurement on the 3D model for *Callogorgia verticillata* in the Cassidaigne canyon [12].

B. *MAPPING CONFIGURATION*

The "mapping" configuration enables very high resolution bathymetry for the study of complex underwater reliefs in rough environments like in canyons, in which non-remotely operated vehicles like AUVs would not navigate in a safe mode or would not navigate so close to the bottom and therefore provide a lower resolution map.

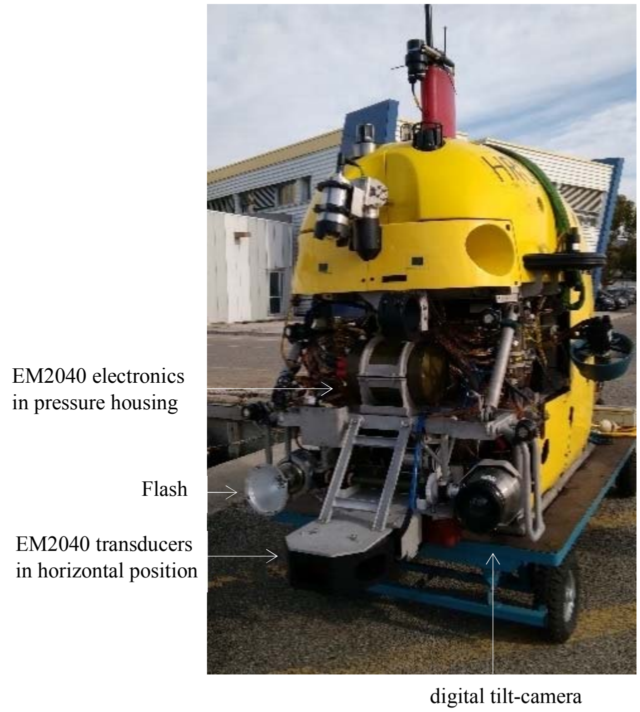

Fig. 12 : *Ariane* in "mapping" configuration

Another innovative feature is the ability to produce 3D acoustic cartography of steep inclines and canyon walls. The vehicle design allows to install the echosounder transducers in tilted positions from nominal horizontal position to a 45° configuration. In 2018, sea trial leads to the 3D mapping of a canyon wall near Saint Tropez that demonstrates the feasibility (Fig. 13). Processing tools and methodology are currently under investigation at Ifremer. First scientific uses are expected in 2019-2020.

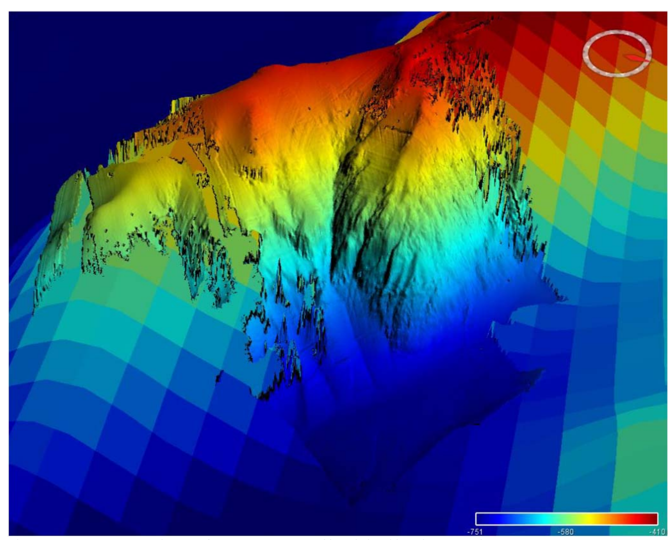
Fig. 13 : 3D mapping of a canyon wall with tilted transducers (ESSHROV2018 cruise, 2018)

Bathymetry raw data are displayed as point clouds in a real time 3D viewer (Fig. 14) that allows a preliminary data analysis and, at the same time, offers a wide-scale perception of the vehicle environment to enhance exploration of unknown areas or the search for sites of interest.

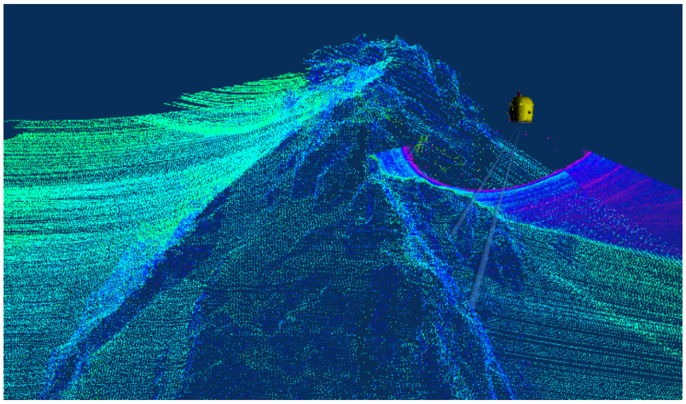

Fig. 14 : print-screen of the 3D viewer with Ariane mapping a rough environment.

The “mapping” configuration enables to combine acoustic survey and visual inspection. As in the “exploration and sampling” configuration, *Ariane* integrates the digital single-lens reflex camera fixed on a tilt actuator, with an associated flash which enables taking photos far from the scene, up to 10 m depending on water turbidity and overall visibility.

V. CONCLUSION

Since its commissioning in 2016, Ariane is a fully operational underwater system that has totaled to date 130 dives, accomplishing numerous tasks down to 2500 m in fields such as benthic ecology, environmental assessment, archeology, and logistic services to deep-sea observatories.

In addition to the scientific results, the first two years of operation enabled to tune and maximize the overall system performance. Further technical developments will now focus on the development of new payloads and operating interfaces on new vessels.

A third payload module is currently being designed, and targets routine maintenance operations on deep-sea observatories such as the ones developed in the European Consortium for Research, EMSO ERIC (European Multidisciplinary Seafloor and water column Observatory). It will integrate a larger tool bay that increases the capacity of carrying tools and allows for extensive sampling.

Furthermore, the AUV mode, based on deployment without any tether linked to *Ariane*, will be adapted to scientific dive scenarios and will offer new perspectives in the years to come.

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