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From manned to autonomous and hybrid underwater systems. A review of existing operational systems, development trends and IFREMER/DCNS cooperative projects

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Abstract :

This contribution will convey 25 years of knowledge and experience build on operational underwater manned submersible and robot vehicles programs.

It will highlight the evolution from manned and remotely-operated robots to autonomous systems, and fleets scenario aimed to address shallow to ultra-deep water stakes and applications, mainly encouraged by the optimization of systems effectiveness, cost at sea for routine operations and technological innovations.

The presentation will emphasis underwater intervention and survey for new fields of application as mineral resources, deep oceans, marine energy ..., illustrated by their TRL and OPEX, and getting few examples of near future trends already handled through close cooperation between IFREMER, key international laboratories, DCNS and other industrial partners.

Keywords : component, formatting, style, styling, insert

I. Existing operational systems from manned to autonomous and hybrid underwater systems

Among the deep underwater intervention means of IFREMER, the French Marine Research Institute, such as ROV *VICTOR 6000*, AUVs *Asterx and Idefx*, Towed Sonar Systems *SAR 6000m and deep sea source SYSIF*, coring system *PENFELD*, *Nautile* 6000m rated manned submarine is the deep sea vehicle which has one of most underwater experiences.

Nautile 2002 © *IFREMER*

Since its operational birth in December 1984, *Nautile* has been engaged in 137 campaigns and 1850 dives. The fourth big overhaul has been realized in 2008, with a global upgrade of several systems and subsystems and a full inspection and control of the main hull, and of the equatorial joint. Between mid 2008 and the end of 2012 *Nautile* has been operated on 160 dives.
Concerning the present and future operational utilization of the submersible, in parallel with regular upgrade of the equipments to maintain the submersible at a high level for scientific operations, there is emphasis on two types of actions: the optimization of the performances of the couple ship / submersible during operation, and the costs reduction of the part of activities dedicated to the infrastructure (maintenance, overhaul,..). The first type is linked to a combined use of the submersible (during the day) and the AUV (during the night). The second type, supported by feedbacks on 25 years of operations, leads to optimize the maintenance program, with emphasis on priority actions and studies on main hull, buoyancy foam and main frame ageing.

1- Context

To carry out fundamental research in various deep sea scientific areas *IFREMER* and the French Navy ship design and building authority named DCN, nowadays DCNS, conceived, developed *Nautile* submarine in 1982 to 1984. First sea trails took place in 1984. *Nautile* reached 6600m depth in diving tests in 1985, and began its operational activity.
It is specially designed to work at 6000m depth for visual inspections and manipulative tasks on seabed sites large as 1 Km2. But in particular cases it is able to run along several kilometers in the fields of its positioning system.

From 1984 to end of 2012, *Nautile* dived 1650 times in all world seas and underwent 4 overhauls, the last one in 2007-2008.
From 1984 to 1999 the activities of *Nautile* were around 100 dives a year.
In 1999, IFREMER began to use the new ROV *VICTOR 6000* in operational activities. From this date the *Nautile* activity decreased to around 50 dives a year. A new lease of life is given now by the association of the *Nautile* (during the day) and the AUV (during the night) in the same mission, allowing increasing the scientific results (with optimized surveys with the AUV) and optimizing the cost (the ship being the expensive part).

IFREMER has two open sea vessels able to deploy *Nautile* at sea: ATALANTE and POURQUOI PAS?, well adapted to the long time scientific campaigns with multidisciplinary capabilities and large areas for scientific activities on board. The two vessels are carrying complete panoply of scientific instrumentation, with multi beam capabilities, and up to date means for data acquisition and processing, and sampling analysis.

ATALANTE

© IFREMER

<u>Main characteristics (year of construction : 1989)</u>

Length / breadth / displacement	84,60 m / 15,85 m / 3550 T
Classification	*Bureau Veritas* : I3/3E classification, ✠ , open sea, ice II, AUT-PORT,
Propulsion - Cruising speed	Diesel electric - 11 knots
Ship's crew – Max passengers	17 to 30 (depending on type of mission) - 33

POURQUOI PAS?

© IFREMER

<u>Main characteristics (year of construction: 2005)</u>

Length / breadth / displacement	107,6 m / 20 m / 6600 T
Classification	*Bureau Veritas* : Class 1, ✠ , special service, open sea, ALP, ALM, ALS, AUT-IMS, AUT - PORT, SYS-NEQ-1, DYNAPOS AM/AT R, COMF-G1
Propulsion - Cruising speed	Diesel electric and DP system Cl II - 11 knots – 64 days
Autonomy	64 days
Ship's crew – Max passengers	40
Scientific area	950 m2

Nautile is operated by *Genavir* Economic Interest Group who assumes the management of *IFREMER's* vessels, systems and equipments. It is a maritime ISM certified French shipping company.
Genavir operates the other *IFREMER's* vehicles as ROV *VICTOR 6000*, Towed Vehicles *SAR 6000 and SYSIF*, and two AUV *Asterx and Idefx.*

2- *Nautile* main characteristics

Weight (ready to dive to 6000m)	19,5 t
Dimensions	Length: 8m Width: 2,70m Height: 3,45m
Hull	2 titanium hemispheres bolted together Inside diameter: 2,1m 3 port holes (diam. 120 mm) 20 electric penetrators on four stiffeners
Crew	3 persons - Pilot + Co pilot + passenger
Dive duration (max / average / average on seabed)	10h – 7h – 4,5h
Security duration	5 days
Efficient energy at 6000m	2 lead batteries: 1 x 37 kWh in 240VDC 1 x 6,5 kWh in 28VDC
Speed (m/s): Longitudinal - Vertical down –Vertical up	3,5 – 1 – 0,8
Payload	200 daN in water
Basket	Volume:: 420 liters Capacity: 200 daN in water
Hydraulic manipulators	Gripping arm with 5 axis Main manipulator with 7axis

3- Maintenance and Overhauls

Nautile is operated by a crew of 8 persons and usually is deployed for diving every day during a campaign.

Initially, the *Nautile* was built with the objective to have a submersible able to operate with a high level of safety and reliability during a long period (time and cycles). This preoccupation has led to the choice of the materials and the importance of the qualification program, concerning in particular major elements as main sphere, buoyancy pack, and main structure that constitute expensive and not easily replaceable parts.

IFREMER and *Genavir* lean on maintenance and evolution specific procedures, finalized and controlled by two independent commissions:

- *Nautile* Safety Commission (CSN): she analyzes and evaluates all points concerning human safety;
- *Nautile* Evolution Commission (CEN): she analyzes and evaluates the evolution files, from the request to the integration, and guarantees the tracing of each evolution.

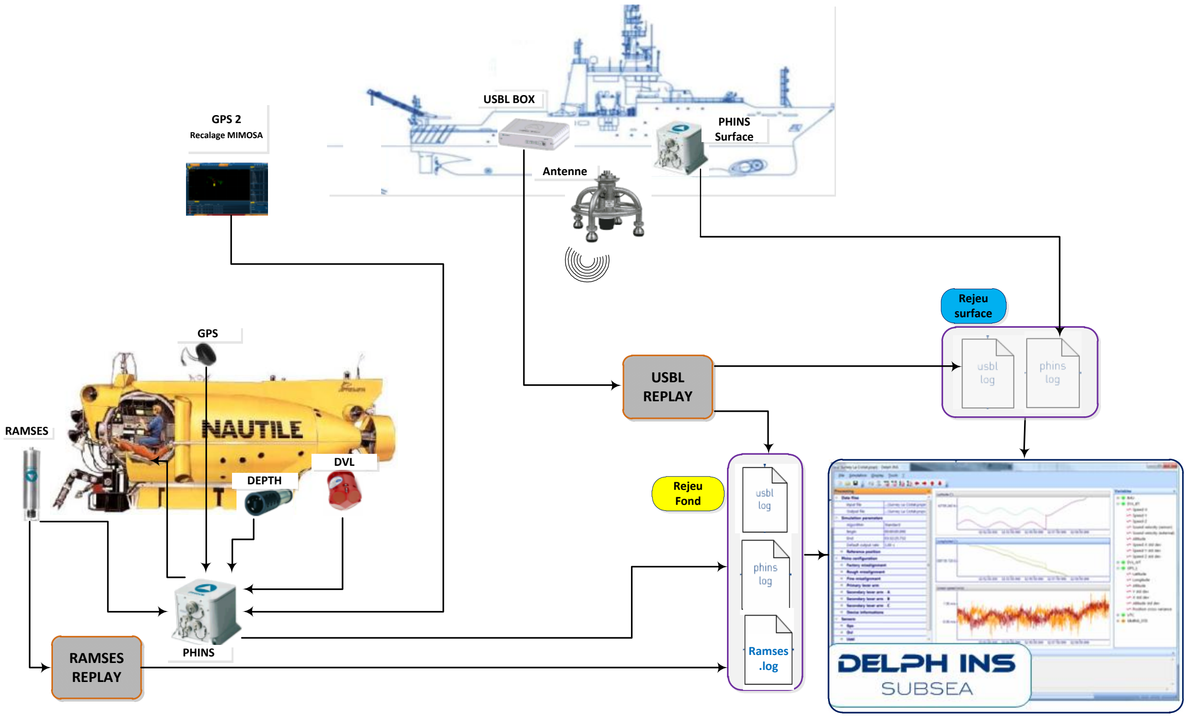
3. 1- Maintenance overhauls

Maintenance program includes daily interventions (before and after dives), monthly interventions (after each campaign for instance), annual interventions (as portholes and hull penetrators controls, sensors calibration, connecting inspections…) and overhauls. So until now, an overhaul has been carried out every 5 years. The table below precise the most important evolutions achieved at the time of each overhaul.

	Year	**Nbr of dives**	**Principal evolutions**
Start of activity	1984	0	
First overhaul	1990	458	- Integration of a new transverse thruster - Video camera Tri CCD - Upgrade of electronic control of the thrusters - Integration of the rescue buoy system
Second overhaul	1995	498	- HMI lights - Data acquisition station first refit - New shot ballast releasable - Electrical architecture refit
Third overhaul	2000-2002	516	- Complete refit of the propulsion (thrusters & electronic control) - Digital still camera with flash - New data acquisition system refit (Acquanaut 3) - DVL integration - New electrical architecture for control command by bus Can integration - Replacing of obsolescent equipments
Last overhaul	2008	210	- Setting up a new electric rudder - 2nd digital still camera Pentax - Video camera HD with hard disk recording

Note: The third overhaul was considered as the mid-life overhaul. Lot of equipments was replaced for obsolescence.

3.2 - Recent evolutions



On the surface vessel: an acoustic antenna is linked to a Box (USBL-Box) which receives from an inertial navigational system PHINS (or Photonic Inertial Navigation System - incorporates Ixsea's Fiber Optic Gyroscope (FOG) technology) outputs position, attitude and velocity data to extremely high levels of accuracy.

On the submersible: An acoustic transducer RAMSES allows the positioning by the surface vessel and the dead-reckoning is carried out by another inertial navigation system PHINS, linked to a Doppler Velocity Log (DVL) and a precise pressure transducer.

3.2.1- New HD video recording network

The objective was to get the same level of quality than our ROV Victor 6000 HD video network, with similar equipments needed to HD video processing of images from mobile and fixed cameras. That was concerning converter, inlaid work, video grid and recorder.

3.2.2- New real time navigation following software

The objective was also to mutualise the data processing and exploitation of the *Nautile* dives, with same equipments and quality than *Victor 6000*. The setting up of the navigation following software “Mimosa 2” allows having in real time in the submersible the corrected trajectory on the bottom, with setting up the existing bathymetry.

3.2.3– New underwater phone

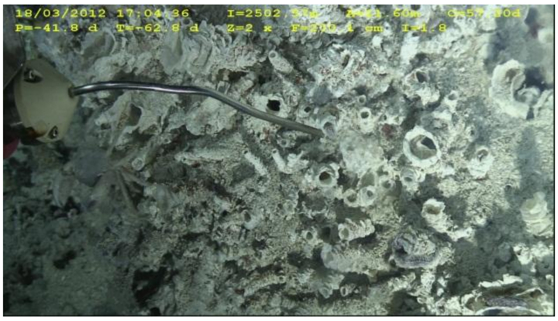
The existing telephone « TUNX » was installed in the submersible since the origin in 1984. It was working well, but the technology was obsolete and the maintenance control would be difficult. We have decided to test in parallel new equipment from German ELAC Company that proposes the same characteristics than the existing one, plus extra functionalities as “SMS” data transmission (allowing automatic transmission of submersible position by the surface vessel).

4. *Nautile* campaigns since the last overhaul

Nautile ended the fourth overhaul on May 2008, after sea trails campaign.
Since this date *Nautile* had been used for scientific missions and for public missions. The table below gives some details.

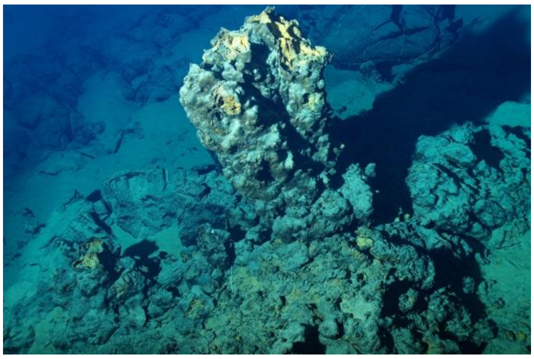
Name	Date	Nber of dives	Seas	Nature of the campaign
ESNAUT	2008	11		Technological tests
BEA – AF 447 research operation	June 2009	1	Atlantic	Public service mission: research of AF 447 Rio-Paris
MESCAL	20-27 May 2010	19	Pacific	Scientific mission
BIG	30 May- 9 july 2010	28	Pacific	Scientific mission
FUTUNA	3-23 September 2010	12	Pacific	Scientific mission
DEMANE	August 2011	20	Atlantic	Scientific mission
MESCAL 2	March 2012	10	Pacific	Scientific mission (1)
FUTUNA 3	June 2012	20	Pacific	Scientific mission (2)
TOTAL :		121		

(1) MESCAL 2: Life in extreme environments. Investigate the biological adaptations and colonization strategies of the endemic fauna of the extreme environment of deep-sea hydrothermal vents, combining in situ chemical analysis, in vivo pressurized experimentation, and in vitro genomic approaches.



Mescal 2 © IFREMER

(2) FUTUNA 3: Recent investigations conducted by international teams and knowledge of fossil sulfide deposits show the importance and diversity of vents and hydrothermal mineralization in the volcanic back-arc basins of southwest Pacific. The Futuna3 cruise aimed to determine its mineral resource potential, achieving, from the *Nautile* dives and AUV, sampling and detailed studies of hydrothermal fields located during Futuna 1&2 cruises.

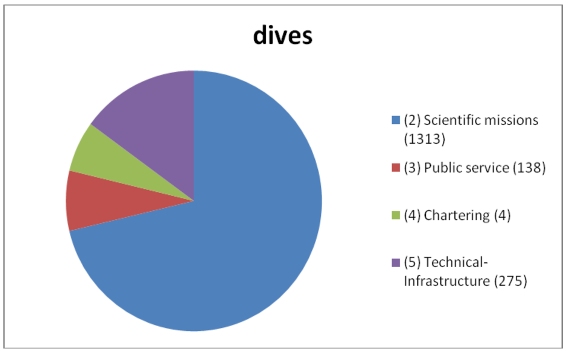


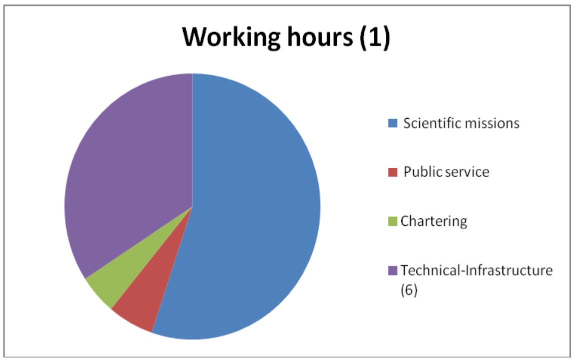
Futuna 3 © IFREMER

5. Feedbacks on 25 years of operations

5.1 Activity

Since it has started its activity, *Nautile* has been operated for many types of missions. The two graphs below are a tentative to draw up first and simple assessment.





(1) : An average of around 7 hours are allocated to a dive

(2) : This is the principal mission of the submersible, for which an annual budget is allocated to *IFREMER* by the French government

(3) : These dives are generally not programmed. They are occurring after an unexpected event coming under public consequences (French, European,..). This was the case of the dives on Prestige Wreck for example.

(4) : The *Nautile* is chartered by private funds (Titanic...).

(5) : These dives are concerning the sea trials needed after overhauls, or even after specific evolutions needed to increase safety or operational capabilities

(6) : Time allocated to technical dives + overhauls only (Each overhaul last around 6 months / 3800 Hours) that represent the periods directly concerning important dismantling and demobilization, without taking into account other technical interruptions, or the time used by the team to make improvements studies when the submersible is not used.

So, if we take into account the dives for technical trials, the time affected to "technical infrastructure" is around 5700 hours, representing almost 50% of the activity.

Another pertinent comment is the following: during a campaign, or a part of a campaign, only allocated to the *Nautile* deployment, the ship could be used 50% of the time for other objectives, considering that the submersible is on deck during the night.

These two last considerations led present and future operational utilization of the submersible.
In parallel with regular upgrade of the equipments to maintain the submersible at a high level for scientific operations, there is emphasis on two types of actions: the optimization of the performances of the couple ship / submersible during operation, and the costs reduction of the part of activities dedicated to the infrastructure (maintenance, overhaul...).

5.2 Optimization of performances: coupling *Nautile* / AUV

The first consideration is linked to a combined use of the submersible (during the day) and the AUV (during the night).

More than 550 scientific expeditions have set out in search of these clusters of hydrothermal sulphides or "smokers". After three decades of exploration on 60,000 km of oceanic ridges, nearly 150 such fields have been identified. Manned submersible, deep sea ROVs and AUVs are currently used on such campaigns. With partnerships between universities and industries around the world, exploration and permit applications are accelerating, in particular in the field of mineral resources. In France, IFREMER and the BRGM (Bureau of Geological and Mining Research) are associated with Technip, Areva and Eramet in the context of a public-private partnership unpublished research. The group has won recently the second of the seven permits issued by the International Seabed Authority, which organizes the exploration potential fields beyond the limits of territorial waters.

Within this context optimization of survey and intervention dives during a same exploration campaign is a key issue to speed up the rush and to setup high resolution maps, with related high definitions ground trough. For Far sites as for example Wallis and Futuna in the middle of pacific, the concurrent use during the same campaign of a wide set of equipments is crucial.

The coupling *Nautile* / AUV proved particularly effective strategies to drive exploration dives. The metric resolution maps drawn by the AUV finally give scientists documents whose resolution corresponds to the actual scale of observation on the merits of the *Nautile*. Running day Dives with *Nautile* and night mapping (in particular with acoustic multibeams and magnetic sensors) with AUV the ship time is then optimized.

In that sense, with vehicles on both sides of the IFREMER underwater systems fleets "family" (fig 5-a), AUVs, as missing link, are "serving" the *Nautile* system heritage.

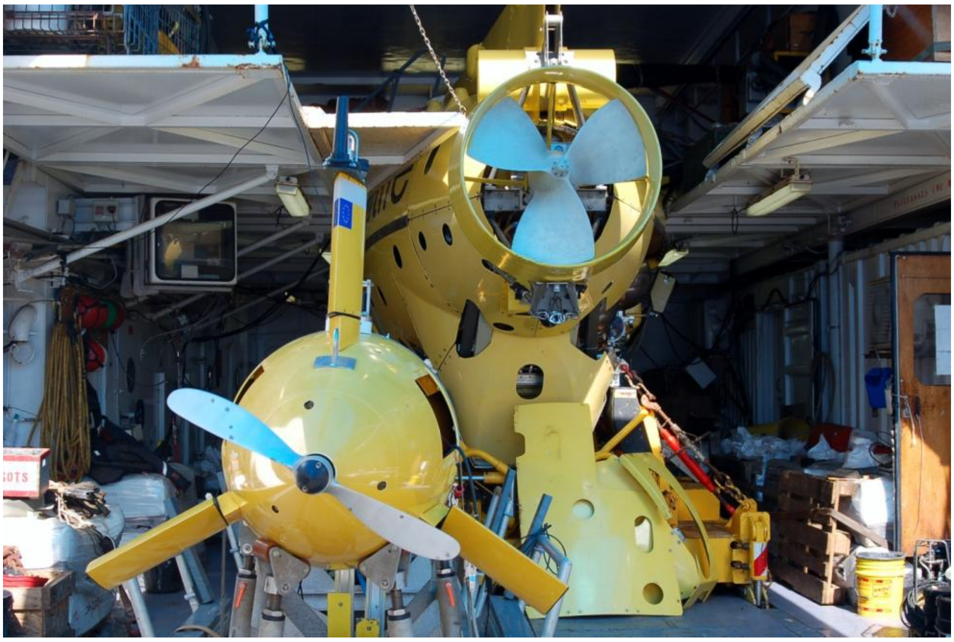


Fig 5-a: Nautile and IdefX AUV on board R/V Atalante during cruise Futuna3 on Mineral resources © IFREMER

6 A new cost effective and innovative 2500m Hydride ROV-AUV

The increasing demand for environmental high resolution mapping and precise intervention has engaged IFREMER to design a new innovative Hybrid Remote operated Vehicle named H-ROV to meet scientific exploration challenges up to 2500m. The system has been designed for a high Technology Readiness Level and an optimized Operational Cost OPEX. The main objective of this new hybrid underwater robotic system (HROV) is to combine the ability to gather high resolution data and perform inspection and intervention tasks while maintaining operational costs to a minimum. The system is designed to be operated in both ROV and AUV modes considering the mission scenario. This will enable wider access by the scientific community to highly specialized tools designed from the outset to meet their goals. The system can be deployed in ROV mode from small size non DP ship up to 2500m depth and is by the way of the OPEX optimization very attractive for industrial applications . Beside the new underwater system itself, a set of integrated services in the field of optical and acoustical mapping have been developed and improved. This presentation reports on the main innovative aspects of the new Hybrid H-ROV system in term of architecture, deployment, energy, control, mapping and intervention services.

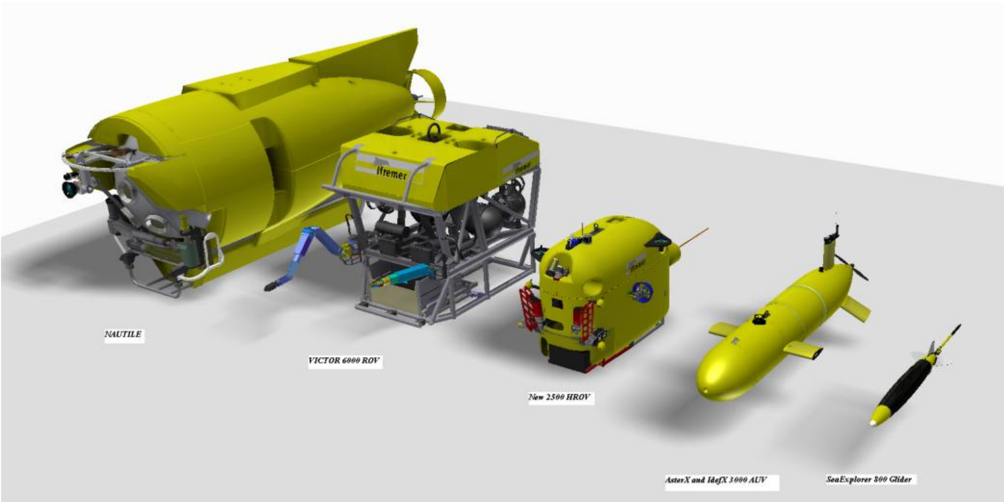


Fig 6-b: IFREMER underwater systems Family © IFREMER

II. Development trends

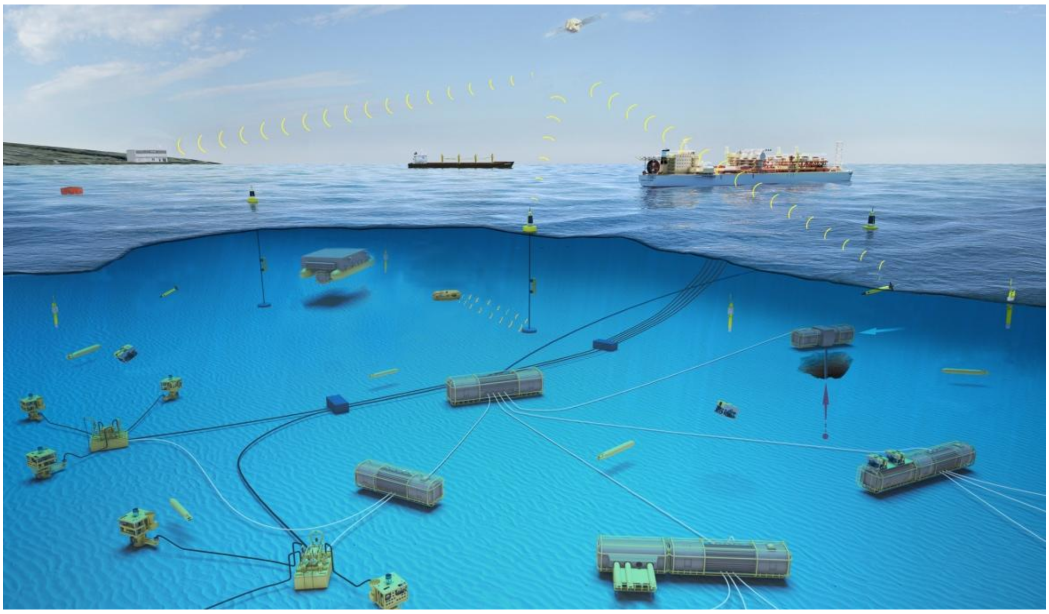


Figure: Future subsea factory by DCNS, subsea power plant and site monitoring system © DCNS

The future subsea factory

The subsea power plant seen by DCNS represents the breakthrough step which will allow further collecting or valuing of mineral resources in very stringent conditions and environments: depth, T°, weather, remote offshore location, extended site.

The main purpose is to relieve the constraints of the FPSO unit afloat and locate the power plant (whole or partially) on the seabed close to the exploration and production means, which are high energy consumers.

System hull design, marinisation and physical integration of on shelf electrical equipments, thermal impacts optimization, connectors, global system architecture, deep sea handling and maintenance equipments, added to requirements in terms of global safety, reliability and long term availability require specific and brand new cutting edge solutions.

In that purpose, DCNS is currently developing a MUST® (Modular Underwater Station) equipment family.

Figure: UPS module © DCNS

Subsea Watcher® by DCNS

The monitoring of the impacts of an industrial activity on the subsea environment at depth > 1000 m (flora & fauna, minerals) is an issue that shall become more crucial in the near future.

Subsea Watcher® is a fully integrated architecture envisioned to ensure a continuous and remote monitoring of the environment and seabed installations.

It relies on specific sensors chosen in respect with the parameters that we intend to monitor (t°, density, oil leaks, seismic, minerals presence in fumes, turbidity, water column characteristics…), integrated on a whole range of carriers, ranging from deriving buoys, anchored buoys, profiling floats or AUVs, with their individual energy storage capacity completed by a energy docking station on site, and organized as a global network of sensors deployed at sea and communicating together. The anchored buoys (*Subsea Linker Backbone®*) also ensure the role of communication network, thus enabling to gather all the information and send them to an operator for real-time monitoring of various parameters underwater and above the surface, operator who shall be located onboard a ship or even on shore. Data extraction and treatment, alert management, steering dashboard for the remote operator, mission repositioning for the carriers are parts of the global solution.

DCNS, based on skills and know-how already used for maritime surveillance, is developing step by step the *Subsea Watcher®* system.

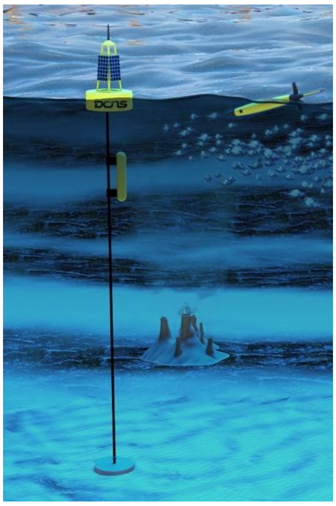


Figure: Subsea Linker Backbone® © DCNS

In addition to the recent breakthrough of IFREMER and DCNS in the technology of homing and docking system (ref § III of the present document), which will enable long term deployment of AUVs on site, DCNS focuses on contact free energy and data transfer, and communication in harsh deep sea environment.

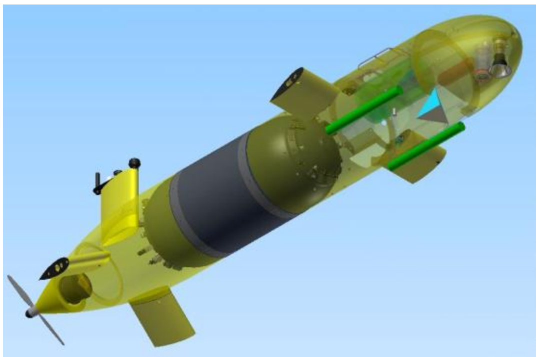


Figure: AUV structure

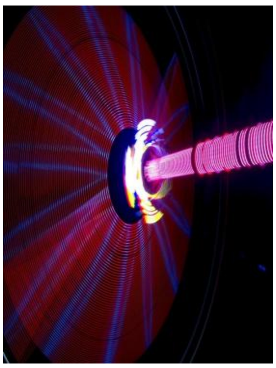


Figure: Contact free high volume Communication and energy transfer

III. IFREMER / DCNS cooperative projects

Since the *Nautile* development, IFREMER and DCNS have worked together to develop new technologies. While pushing further the AUV performances through different projects and co-development with partners, in the fields of architecture, embedded intelligence, energy storage, high tech payload integration, communication means, both companies are exploring together a new configuration for subsea vehicles, for instance the AUV homing-docking.

1. Docking- homing for AUV

Within the scope of the cooperation agreement (MOU) signed between both companies, IFREMER and DCNS launched a common project demonstrating techniques for an AUV docking in an underwater, vessel-born, moving platform.

IFREMER's AUV asterx®, a 4.5m, 800kg and 2800m depth rated vehicle, was adapted in order to host the DCNS guidance payload called SCOM. The payload instruments allow the AUV to be guided towards the docking station by active acoustic positioning, and to home into the docking station by recognizing LED patterns mounted on the docking station.

The docking station was built specifically for the project, its design being based on the analysis of platform movement, AUV piloting accuracy and guidance measurement tolerances.

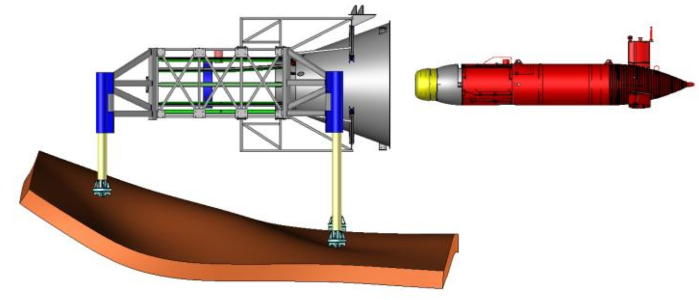


Figure: docking system structure © *DCNS*

During the maneuver, the AUV remains in a wait circle until an acoustic command triggers the approach towards the vessel. The ultra-short baseline device on the docking structure determines relative position of the AUV payload pinger and sends continuously updated target positions back to the vehicle via the data link of the same acoustic device. The target position of the acoustic approach phase is defined within the optic range of the optical homing system. The vessel and docking station move at a constant velocity at two knots below AUV speed. The payload's recognition video system of the LED pattern and the extraction of guidance commands, does then lead the AUV into the docking station.

IFREMER's tasks in the project were to provide, adapt and operate the Asterx® AUV, accomplish the physical and logical integration of the SCOM payload, and implement the mission control concept handling the payload guidance input. The IFREMER team contributed with the functional concept of the docking maneuver, with the tolerance analysis determining the dimensions of the docking station entrance cone. IFREMER also provided risk analysis and onboard exception handling designed to secure the critical dive phase only a few meters below the vessel. The mechanical shocks happening when the AUV enters the docking station were also analyzed and led to a number of mitigation actions.

The main modifications on the AUV system are:

- the physical integration of the SCOM payload in the place of the standard nose section, including fitting of a shock absorber between the payload housing and the vehicle structure;

- the suppression of front planes and modification of the control laws in order to steer the vehicle with the remaining three planes in the vehicle aft section; this part of the AUV does not enter the cylindrical housing of the docking station;
- the software control system was enhanced by a new mission mode allowing navigation control by an external device called the "backseat pilot". The new software architecture allows the backseat controller to take over the navigation control of the vehicle, validating and forwarding the payload guidance data in a specific docking mode;
- the vehicle safety is still handled by the primary vehicle controller; a set of specific exception criteria and security actions were implemented to minimize risk especially in the final approach phase behind and under the vessel.

The project was led by a joint IFREMER and DCNS team that worked in a very tight time scale of only six months, and produced all the expected results. The outcome values the engineering skills of both companies as well as the capability to work in a joint team and to adapt to the respective partners methods and constraints.

The final sea-trials, resulting in a series of successful docking maneuvers, was prepared by progressive validation steps on a simulation test bench and in harbor trials. With a project kick-off in January 2014, the video footage proving the successful operation at sea was brought back to shore on July 18th, 2014. Further ongoing projects building up on the docking technology are now being planned for the new future.

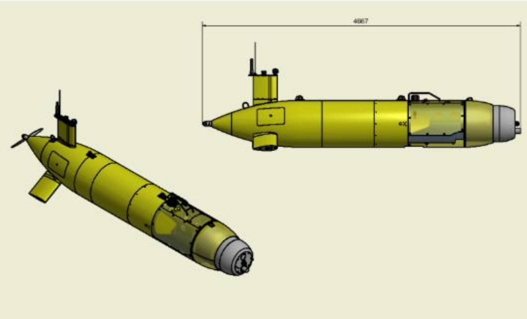


Figure: CAD design of the modified *Aster*^{x} ®AUV

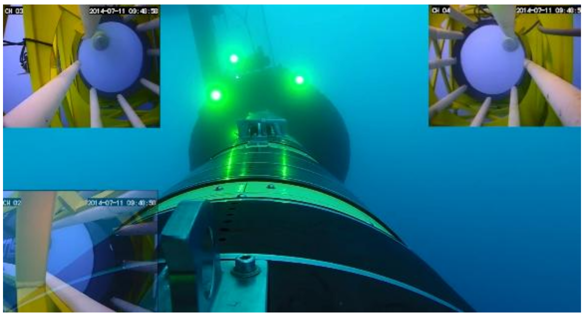


Figure: AUV in docking maneuver

IV. Conclusions

Concerning the present and future operational utilization of the submersible, in parallel with regular upgrade of the equipments to maintain the submersible at a high level for scientific operations, there is emphasis on two types of actions:

- the optimization of the performances of the couple ship / submersible during operation by combining the use of the submersible and AUVs,
- the costs reduction of the infrastructure maintenance and overhaul by optimizing the priority studies on main hull, buoyancy foam and main frame ageing.

In addition a cost effective hybrid robotic system has been developed, the H-ROV, to complete IFREMER's underwater fleet for the exploration up to 2500m depth.
New stakes are now tackled, such as continuous and remote monitoring of deep sea activities and environmental parameters, long period deployment of AUV on site, aiming to further develop AUV capabilities and life expectancy. In that respect a new breakthrough has been reached by IFREMER and DCNS and the homing-docking of AUV.

V. Contributors and references

1- Contributors

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IFREMER, through its research work and expert advice, contributes to knowledge of the oceans and their resources, to monitoring of marine and coastal environments and to the sustainable development of marine activities.
To these ends, IFREMER conceives and operates tools, including all underwater systems and large-scale mobile facilities and equipment (seismics, penetrometer, etc.), for observation, experimentation and monitoring, and manage the oceanographic databases. IFREMER performs targeted applied research to address the questions posed by society (climate change effects, marine biodiversity, pollution prevention, seafood quality etc.). Results include scientific knowledge, technological innovations, and systems for ocean observation and exploration.
IFREMER works in a network with the French scientific community, but also in collaboration with private and public partner organisations, centred on large international programmes, on French overseas regions, southern Mediterranean coast and targeted countries (United States, Canada, Japan, China, Australia and Russia).
Created in 1984, IFREMER is a public institute of an industrial and commercial nature (EPIC). It is supervised jointly by the Ministry of Higher Education and Research and the Ministry of Ecology, Sustainable Development and Energy.

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DCNS designs, builds and supports submarines, combat surface ships and mission-critical systems, incorporating the most advanced technologies, as well as associated systems and infrastructures, and offers a full range of services to naval bases and shipyards. The Group has also expanded its development into marine renewable energy sector, developing tidal, thermal, wind and wave energy systems, conceiving and implanting marine energy production farms trough out the world. The Marine Energy and Infrastructures Division hosts as well the Blue Growth Incubator, as a new growth business area focus. DCNS now targets the new maritime activities such as deep subsea resources exploration, by providing its strong knowledge and expertise of the marine environment – such as the safety and security of complex systems in confined environment, the combination of mechanical and electronic technologies together with embedded intelligence and cutting edge command system, that are particularly relevant for the underwater deep sea activities.

2- References

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