Underwater Intervention Robotics: An Outline of the Italian National Project MARIS

By the MARIS Team

G. Casalino[1], M. Caccia[2], S. Caselli[3], C. Melchiorri[4], G. Antonelli[5], A. Caiti[6], G. Indiveri[7]
G. Cannata[1], E. Simetti[1], S. Torelli[1], A. Sperindè[1], M. Bibuli[2], G. Bruzzone[2], E. Zereik[2], A.Odetti[2]
J. Aleotti[3], D. Lodi Rizzini[3], F. Oleari[3], G. Palli[4], U. Scarcia[4], L. Moriello[4], E. Cataldi[5]

Abstract - **The Italian national project MARIS (Marine Robotics for InterventionS) pursues the strategic objective of studying, developing and integrating, technologies and methodologies enabling the development of autonomous underwater robotic systems employable for intervention activities, which are deemed progressively becoming typical for the underwater off-shore industry, for search-and-rescue operations, as well as for underwater scientific missions. Within such ambitious objective, the project consortium also intends to demonstrate the achievable operational capabilities at a proof-of-concept level, by integrating the results within prototype experimental systems.**

I Introduction

Research activities in autonomous underwater robotics have been so far mainly focused on autonomous underwater vehicles (AUV's) performing exploration and observation missions, with important applications in the fields of oceanography, marine geology, archaeology, environmental sciences, as well as security applications.

1 - ISME, Genova node at DIBRIS, University of Genova, Italy
2 - CNR-ISSIA, Genova node, Bari, Italy
3 - DII, University of Parma, Italy
4 - ISME, Bologna note at DIIEI, University of Bologna, Italy
5 - ISME, Cassino node at DIE, University of Cassino and Southern Lazio, Cassino, Italy
6 - ISME, Pisa node at DII, University of Pisa, Italy
7 - ISME, Lecce node at DIE, University of Salento, Lecce, Italy

Within these fields the need for autonomy naturally emerged for different reasons: a) need of avoiding the use of umbilical cables in force of the maneuvering problems they generally pose; b) need for achieving operational efficiency at high depths, without resorting to highly risky and costly manned vehicles; c) need for faster and adaptable means for environmental monitoring and security applications; thus by even proposing cooperating multiple AUV's.

Since fundamental aspects, like for instance localization, communication and vision technologies, are much more difficult to be tackled in underwater than within ground (and even within space environments) the research in underwater vehicle autonomy has always also faced such problems; till having achieved all a set of now available results that lead to different successful demonstrations within the above fields.

However, another important field in autonomous underwater robotics is the so-called Autonomous Underwater Intervention field; where operations like grasping, manipulation and transportation activities, as well as assembly/disassembly ones, are the main issues to be faced.

It has been however a matter of fact the research on Autonomous Underwater Intervention did not registered the same intensity of the vehicular field; thus remaining for a number of years confined within few, even if significant, research projects launched in the nineties. Certainly this occurred because executing even semi-autonomous underwater interventions is not at all an easy task; but probably also because the needs for autonomous interventions were previously not so evident, as it instead seems to be nowadays. As a matter of fact the dramatic accident recently occurred in the Gulf of Mexico, and the previous crash of an airliner in the Atlantic Ocean, have very much contributed in evidencing the importance of the eventual availability of smart underwater intervention robots. Such emerged needs now seem having strengthen also other needs, previously left a little latent; such as those that can be now found in the high depth off-shore industry (plant/infrastructure maintenance and inspection, and possibly fabrication); or the emerging need for underwater mining; or even the need for enhanced underwater rescue capabilities, which can be expressed by both civil and military organizations; as well as the needs coming from the marine-science community (oceanography, marine biology, geology, archeology, etc.) which might sensibly benefits from the availability of robotized interventions means in their activities (excavation, coring, handling scientific instruments, sample collection, etc.) at increasing depths; and finally, also the needs that might come from the professional diving community; where similarly to what is currently proposed for the future grounded factories, even a symbiotic undersea human-robot cooperation might be envisaged .

Accordingly with the above considerations, the research in autonomous underwater intervention robotics is therefore now registering a renewed non-negligible impulse; probably also favored by the availability of several of the results and technologies which have been developed for underwater monitoring-only missions; where fundamental topics like underwater localization, communications, optical and acoustic imagery, guidance and navigation, mission planning and mapping, etc., seem now ready for also supporting the renewed research interests on autonomous underwater intervention systems.

Within the above outlined framework, the Italian National project MARIS has originated as the joint initiative of six Departments of the Universities members of the National Inter-University Centre ISME ("Integrated Systems for the Marine Environment") and the unit of Genoa of ISSIA (Institute for Studies on Intelligent Systems for Automation) of CNR

(Italian National Council of Research).

The two institutions qualify for their long-term research experience in the application of ICT to the marine environment, with particular interests in Underwater Robotics, intended comprehensive of all its methodological, technological, and applicative aspects. The project consortium also includes an additional University Department, which has been selected for the highly qualified contributions it can provide to the MARIS objectives. In this framework, the MARIS consortium has in fact established the strategic objective of further developing and integrating the main technologies and methodologies enabling the realization of autonomous systems for underwater manipulation and transportation activities; which are in perspective deemed having strong chances of becoming typical for all previously mentioned underwater application.

Within the project the consortium also intends to provide proof-of-concept demonstrations of the achievable abilities, by integrating the results within prototype autonomous floating vehicle-manipulator systems realized within the consortium itself

II The Project General Objectives

To the aim of the above stated strategic goal, some advances regarding the main technologies and methodologies to be integrated, must however be formerly achieved; in particular as regard the following topics:

- Reliable guidance and control of the floating basis (during long-range motions) on a multi-sensory basis; that is via the integration of inertial sensors, Doppler velocity meters (DVL), external acoustic supports to localization (USBL or SSBL); and possibly via real-time SLAM techniques based on sea-floor observations.
- Stereo-vision techniques and systems, devoted to object recognitions, also including their

position and pose estimation.

- Reliable grasp, manipulation and transportation, of objects by part of manipulators operating from floating basis, that is automatic reasoning for gripper pre-shaping, in turn integrated with appropriate reactive control techniques (based on visual, force/torque and possibly tactile sensing) coordinating the he whole system motions (vehicle, arm, gripper).
- Coordination and control methods for large object grasp and transportation by part of cooperative floating manipulator systems, based on an (as much as possible reduced) information exchange among the agents.
- High-level mission planning techniques, including the automatic decomposition and distribution of cooperative tasks among the agents.
- Underwater communication techniques among the agents (on an acoustic low-bandwidth basis, when far each other, possibly on an optical high-bandwidth basis, when closer) to the aims expressed by he previous points.

The activities regarding further development such technologies and methodologies are obviously all targeted to the general objective of enabling dexterity, agility, and internal coordination capabilities to be exhibited by individual floating manipulators (i.e. internally to the aggregation vehicle-arm-gripper); but with the ambitious additional objective of also exhibiting adequate cooperative capabilities, whenever required to operate within a team of them.

A further objective is instead relevant to the design and realization of prototype systems, allowing the experimental demonstrations of the integration of the results from the previous objective

III THE PROJECT OBJECTIVES WITHIN THE STATE OF ART

The place occupied by the MARIS project within the currently achieved international state of the art is hereafter described, with reference to the various topics composing the project itself.

1. *Control of individual floating manipulators*

First experiences in equipping AUV's with manipulators, date back to the nineties, when the AUV's ODIN (at University of Hawaii) and OTTER (at MBARI) were equipped with arms with very few degree of freedom; and later when the AUV VORTEX (at IFREMERE) was endowed with a 7 d.o.f arm.

Then, at the end of the nineties, the EU funded AMADEUS project (Lane et.al. 1997) represented a step forward in the coordination of robotic structures, in force of the realization of an underwater dual-arm work-cell exhibiting cooperative capabilities in manipulating objects grasped by both the arms (Casalino et al., 2001). Despite operating from a fixed base, the system de-facto allowed the development of one of the first coordination techniques, whose effectiveness was at that time demonstrated by different underwater experiments.

Slightly later, within the SAUVIM project at University of Hawaii (Yuh et al., 1998; Yuh & Choi,1999; Marani &Yuh, 2014) a large AUV was endowed with one of the same type of arms of the AMADEUS work-cell, which employed vehicle-arm coordinated control techniques partially derived from those of the AMADEUS system.

In both AMADEUS and SAUVIM it was however a winning setting the introduction of a clear separation between the roles of the higher levels of kinematic control, devoted to motions coordination, and the dynamic control lower ones, more simply used for tracking the velocity references real-time provided by the higher kinematic levels. Such hierarchical decomposition has later greatly facilitated the further development of more advanced coordination techniques for floating manipulators.

To this regard the research has almost always adopted such paradigm, by consequently addressing the efforts on dynamic control aspects, from one side, toward the development of different specific dynamic control techniques with various levels of sophistication (see for instance the book (Antonelli, 2006); while from the other addressing the efforts toward further developments of kinematic based control techniques devoted to vehicle-arm motions coordination problems. As it regards these lasts, the overcoming of some a-posteriori noted limitations exhibited by the techniques derived from those of AMADEUS (i.e. the fact that, since operating by switching among different coordination schemes; they were actually tending to proliferate) was successively allowed by the introduction of the so-called task-priority based kinematic control techniques (Antonelli & Chiaverini, 1998a,b); that were later organized into a modular and computationally distributable form (Casalino & Turetta, 2003; Casalino et al, 2005); that are now also including the management of tasks of inequality type (typically imposed by system safety requirements, operability ranges, obstacle avoidance needs, etc.) to be generally achieved with higher priorities, even with respect to the mission purposes (Casalino et.al, 2010; Casalino et al., 2012).

The resulting algorithmic framework for such kinematic layer is actually very simple, computationally efficient, and also capable of automatically adapting to changes in the task priorities, possibly dictated by changing control objective sets and/or operational contexts, without requiring any structural change. Moreover the possibility of assigning different priorities to the mobility of the internally composing mechanical parts (i.e. the vehicle, the arm and the hand) is also allowed.

As a matter of fact the earlier version of such algorithmic framework constituted the supporting kinematic control layer which allowed the agile control and coordination of the floating manipulator TRIDENT (Simetti et al. 2014) developed within the recently closed homonymous EU funded project (Sanz et al. 2012)

Currently, activities devoted to the extension of such framework also toward the ease management of interaction control aspects at gripper level, are currently within the research scopes of MARIS; together with the complete ruggedizing of the associated real-time Sw packages.

Such activities are meanwhile also in the scopes of other two EU funded projects; namely the DEXROV project (Gancet, et al. 2015) and the very recently launched ROBUST project; both focused on the employment of autonomous intervention robots within underwater oil&gas and sea-floor mining applications, respectively.

Quite obviously the employment of the above outlined task-priority based kinematic control techniques requires the integration with everything necessary for the extraction, from the sensory apparatuses endowing each system, of the useful information for their closed-loop functioning; and in particular the following already mentioned ones: object recognition and pose estimation via stereo-vision; real-time grasp planning; integrated force-torque-tactile (and also vision) sensing; guidance and control for long-range motions; localization via integrated inertial and acoustic sensing; ambient reconstruction via SLAM based techniques; acoustic communication for long distances, and possibly optical ones for short range.

The state of the art of such aspects, once clustered into three substantially homogeneous topics in relationship with the MARIS scopes, can be summarized as follows

2. *Object recognition, pose estimation, and grasp planning*

In the underwater field a growing interest toward the use of artificial vision, both stereo and mono (Nicosevici et al., 2009; Campos et al., 2011) has been recently registered.

For the recognition of underwater objects, monocular vision has actually been formerly suggested, based on detections of invariant features with respect to the observation point (Isaac & Srivastava. 2010). However, the stereo-vision technology, since enabling the generation of three-dimensional object models from disparity images (Brandou et al., 2007; Campos et al., 2011) has been eventually considered with greater interest. In this case perceptual data are interpolated, filtered, and then split into a suitable topological representations facilitating the object recognition and its pose estimation, even under conditions of partial visibility; thus also facilitating the planning of the grasp of objects of interest.

For grasp planning, the classical metric of robustness (Ferrari & Canny, 1992; Borst et al. 2003) can be efficiently integrated within a stereo vision system, with criteria capable of also indicating, whenever possible, the preferential grasp directions and hand pre-shaping (Aleotti & Caselli, 2010).

Moreover the availability of a 3D model of the object can be used for taking into account, when planning the grasp, of possible constraints directly related with the grasping task itself, such as for instance the presence of surface portions to be kept free, other than the preferential directions of approach (Aleotti et al. 2012), especially when conditioned by the possible presence of obstacles in the scene (Berenson et al., 2007). Activities related with the development of the Hw architecture and real-time Sw for an underwater stereo vision systems allowing 3D model reconstructions, pose estimations and grasp planning, for most typical types (templates) of objects encountered within underwater environments and/or plant infrastructure, represent they also a fundamental active part of the research within MARIS. (Oleari et al., 2015; Kallasi et al., 2015; Lodi-Rizzini et al., 2015)

3*. Integrated force-torque and tactile sensing*

The problem of providing the robots with the sense of “touch“, is fundamental in order to have the possibility of eventually implementing fine and dexterous manipulation tasks; since the feedback from tactile data may enable the detection and the safe control of the interaction of the robot with object. Tactile sensing technology has till now received significant attention only for terrestrial applications, and the studies about tactile sensors for underwater applications has tehrefore been, since few years ago, quite limited (Cannata & Bruno,1999; Tan. et al., 2008; Kampman & Kirchner, 2012); mainly because, even at low depth, water pressure can significantly affect the performance of systems based on the transduction devices commonly used at sea level, where the atmospheric pressure compensation need can generally be neglected.

Part of the consortium has been involved in the recently closed EU funded project ROBOSKIN, devoted to the study and development of distributed tactile sensors for ground and/or space applications. Within MARIS the investigations regarding the possible extension to the underwater field of the technologies developed within ROBOSKIN, based on capacitive transduction, are currently very active (Muscolo & Cannata, 2015**)** with the aim to develop distributed tactile sensors to be integrated within the underwater grippers (possibly working in synergy with miniaturized, of intrinsic-type, force/torque sensor already installed at the gripper by the partnership of university of Bologna) and possibly even distributable on the arm-link surfaces, as a whole-arm artificial underwater skin.

4. *Guidance, navigation, control, ambient reconstruction, localization and communication*

Also the GNC architectures for vehicles long-range motions allows to functionally distinguish among the subsystems relevant to dynamics (Control), its kinematics (Guidance) and its motion estimation (Navigation). Although the GNC literature for individual non-manipulative vehicles is large (Fossen, 1994; Roberts & Sutton Eds., 2006), this is not the case for teams of cooperating floating manipulators (especially when strictly cooperating, as briefly outlined in the next point 5).

For this reason, the relevant activities within MARIS are currently along four main directions, each one starting from the current state of the art, as hereafter indicated.

Modeling and identification techniques originally developed for single vehicles (Caccia et al., 2000) have to be extended to the case of the floating manipulators, for low level dynamic Control purposes.

The problem of environmental reconstruction is instead tackled via SLAM techniques exploiting computer vision and sensor fusion (Ferreira et al. 2011).

As for localization, traditional techniques are to be used, based on distance and bearing measurements, in case of costly employment of USBL systems, or based on acoustically obtained distance information from several points (Caiti et al. 2005), or even from a single point, as in (Arrichiello et al. 2011; Parlangeli et al., 2015; (Indiveri et al., 2016). Since these lasts techniques, especially within underwater cooperative contexts, are strongly dependent on the adopted acoustic communication system and related architecture and protocols (Caiti et al. 2012), their performance optimization represents an additional important intensive activity within the MARIS scopes.

5. *Coordination of cooperating floating manipulators.*

As already mentioned in the introduction, the MARIS scopes include investigation about the perspective possibility of also enabling a couple of underwater floating manipulators to cooperate in manipulating and/or transporting a common object, mainly when it cannot be handled by a sole agent, as it appears roughly sketched in fig. 1.

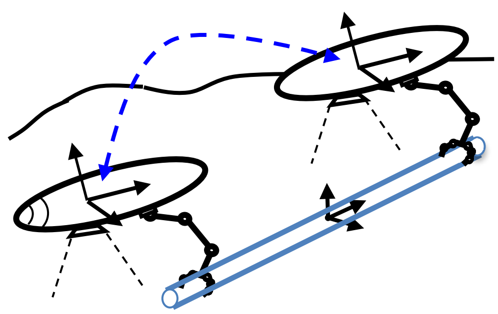

Fig. 1: Sketch of two strictly cooperating underwater floating manipulators

In this context cooperation has to be intended existing also during the approach phase to the object; when, still in absence of manipulative operations, the agents must however maintain a certain level of coordination; and where such coordination, from being of loose type at the beginning of the approach phase, then progressively becomes more intensive in correspondence of its final part, when the agents must finally work close each other; by the way while also avoid to collide. We can therefore speak about weak coordination at the beginning of the approach phase; and of strict coordination at its end. Note however how the weak coordination also realizes when an agent must transfer a grasped object to the other; or also when they must coordinately navigate to reach a common operational zone.

As it can be easily argued, both cases however require each agent exhibiting suitable agile and dexterous operative capabilities; thus further motivating the emphasis that has been formerly assigned to all these aspects for individual agents.

For what concerns the weak coordination, we can further note how it appears closely related to what is also required for AUV's teams used for non-manipulative tasks (i.e. distributed patrolling, sampling, exploration, etc.); for which a wide literature now exists (see for instance chapter 9 of (Antonelli, 2006)). In this area it appears remarkable the fact that also the most recent and most effective proposed techniques (Antonelli & Chiaverini, 2003a,b; Antonelli 2006) actually gain their efficiency from being they also based on priority task concepts and relevant algorithmic structure; which are in turn structurally similar to those employed for the redundancy solution within generic kinematic chains; and thus bringing into evidence how the internal coordination within single floating manipulators, as well as the external ones to them, whenever accomplishing weak cooperative tasks, can therefore be located, at least in principle, still within a common conceptual and algorithmic framework.

For what concerns strict cooperative tasks, it appears even more remarkable the fact that they also can be traced back to the same conceptual and algorithmic task priority framework, developed for individual floating manipulators (for strict coordination between grounded mobile manipulators, this was formerly noted within (Simetti et al., 2009)); however provided the agents can real-time share (as on the other hand is also required for weak coordination tasks) at least the minimal amount of data deemed strictly sufficient for guaranteeing the conflict less executions of cooperative tasks.

The extension to the decentralized cooperative case of the overall task priority based algorithmic framework, is currently at an encouraging stage of development within a suitably devised structuring, mainly oriented to reduce as much as possible the mentioned need of data exchange for conflict less cooperation.

IV THE PROJECT CURRENT ACHIEVEMENTS

Within the project, methodological research activities are made running in parallel with the integration ones. With regard these lasts, fig. 2 shows a CAD representation the advance AUV, named R2, which has been prepared and made available by the partner CNR-ISSIA-Genova node, once integrated with of one of the 7-dof arms instead realized within the ISME-Genova node partnership.

This represents the first one the two systems that planned to be realized, with the second one currently under completion. The R2 vehicle is about 300 Kgs in air and neutral in water. The arm is instead 30 Kgs in air and about 10 Kgs in water.

The successive image of Fig. 3 instead reports about the physical assembly of the first prototype, now also endowed with the stereo vision sub-system designed and realized by the partnership of University of Parma (Kallasi et al, 2015); other than showing the dexterous gripper equipped with intrinsic forced/torque sensors, designed and realized by the partnership of the University of Bologna (Palli et al., 2014, 2015)

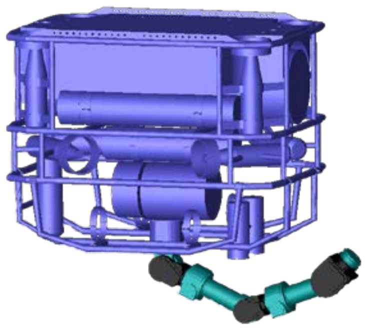

Fig. 2: A CAD representation of the first prototype of underwater floating manipulator

Fig. 3: Assembly of the first prototype of underwater floating manipulator

The system is obviously also comprehensive of the overall Hw and Sw real-time architecture implementing the most essential parts of the algorithmic tools resulted from the achievement of objectives 1, 2, and 3, of previous section.

The integration activities that lead to the first system prototype have required an extensive effort in terms of time and man-power (namely most part of the authorship of this paper), with a considerable part devoted to the Real-time Sw coding and interfacing (mainly via ROS, apart the hard-real time parts internal to the arm and vehicle control levels) of the various resulting Sw processes (kinematic control layer and sensing processes) and to the different separate functionality and validation tests, which have been performed on each composing subsystem. This before progressively proceeding toward their integration, and also before finally performing the validation trials in a pool environment; where good quality performances during individual grasping were exhibited by the prototype.

In particular, Figg. 4a,b show the prototype system while autonomously grasping a pipe during the mentioned pool trials; and video clip can be seen at the link (**LINK TBD)**

At present times, in parallel with the on-going realization of the second prototype system, the activities regarding the extension to the decentralized cooperative case of the same task-priority based coordination and control techniques internally employed by individual agents, have however progressed, even if on a methodological-only basis.

Fig. 4: Underwater view of single-agent experimental grasp operation

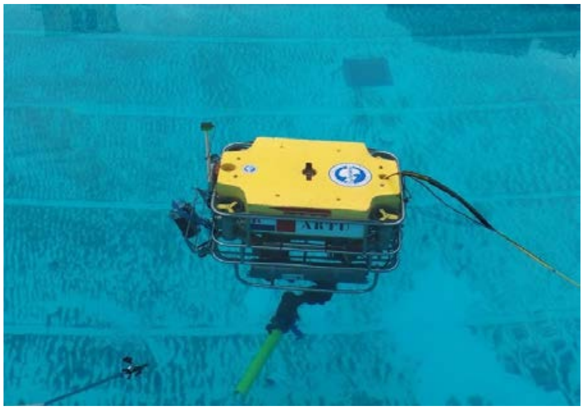

Fig. 5: View from surface of single-agent grasp operations

In particular, to this regard the attention has been mainly focused on the case of strict cooperation, to be exhibited by two agents when manipulating and/or transporting a shared grasped object.

In this case, in order to avoid the already mentioned possibility of conflicting situations, and particular also in order to avoid the possible induction of uncontrolled object stresses, the vehicle and joint velocity *commands* (i.e. reference signals) provided to each agent (by part of their individual task-priority based kinematic control layers) must at each time instant translate themselves into the *same* Cartesian velocity separately desired for the object frame, by part of each involved agent; velocity that in turn must also converge toward the one that is, at each time instant, is required for having the shared object asymptotically reachibg its final position, as ultimately required the mission purposes.

At least in principle, satisfying to the above requirements would certainly be possible in case the agents were allowed to rapidly exchange all the information needed for de-facto transforming the decentralized problem into a centralized one, to be at each time instant solved by each agent on the basis of such complete and totally shared information set.

Since in practice such ideal situation cannot obviously be considered (apart its complexity, principally due to communication bandwidth limitations, even in ground applications; and thus even more within underwater ones), for the time being the hereafter outlined best-effort decentralized coordination policy (Simetti et al., 2015 a,b; Manerikar et al, 2015) has been therefore proposed, investigated, and tested on a simulative basis.

a) At each time instant, the task-priority based control layer of each agent produces its own arm-joints and vehicle velocity commands, as if it was the sole transporting agent; and therefore by solely keeping into account its own internal list of prioritized tasks. This leads, for each agent, to the associated desired Cartesian velocity for the object frame. Such separately produced object frame reference velocities may however differ each other, just whenever at least one of the agent is still engaged in achieving its own higher priority objectives (safety conditions, operability ranges, obstacle avoidance, etc.). And in this cases the two separate velocity tracking requests, whenever applied, would obviously result into a conflicting situation and into unwanted stresses of the shared object. Thus, to the aim of avoiding such possible occurrences, the following other step is executed *before* applying any reference command by part of each agent.

b) The produced individual object-frame reference velocities are exchanged, and their weighted mean separately evaluated by each agent.

c) Such mean is then used as common reference velocity for the body frame, and re-assigned as the highest priority task to each agent; that on this basis will separately re-compute, and at this stage the apply, its own vehicle and arm-joint velocity references.

As it can be easily realized, the above outlined best-effort coordination policy de-facto arises as a reasonable way for allowing both systems to separately carry out their own safety and operational-enabling tasks, while also avoiding uncontrolled object stresses; and in any case without requiring any unfeasible amount of information exchange at each sampling period (in fact, only six real numbers have to be exchanged, even if in a full duplex way).

For the time being extensive simulation campaigns provided quite encouraging results, to be hopefully later confirmed via experimental trials, once the second system prototype will be available.

To this regard (cooperative experimental trials) a risk however exists whenever, with acoustically performed data exchanges, the available state of-the-art modem technology might however not be able to support the required full-duplex communication at a reasonable rate (reasonable for control purposes) despite being relevant to solely six real numbers to be exchanged. Thus, by keeping into account such possibility of this, actually not so unlikely, investigation activities regarding the alternative use of high bandwidth optical modems (Cossu et. al, 2013) are currently they also running in parallel with all others ones. Note however how, in this situation, the physical distance between the cooperating agents should however not exceed few meters (typically less than five), which are however still sufficient for covering the most part of the foreseeable cooperative manipulation and transportation tasks. Also note how, still in this case, an acoustic link could however be maintained, for the possible exchange (with much reduced rates) of "tactical information" of semantic significance (i.e. mainly of symbolic type) for the overall coordinated mission. This however represents an additional aspect that will be addressed by the project in the near future.

For the time being the set of images in Fig. 6 report about different stages of a simulated transportation mission and final precise positioning, of a pipe carried out by two cooperating systems (the pipe-icon appearing in the bottom-right represents the final goal position to be reached; rendering has been obtained via the open-source package UWSim (Prats et.al 2012)

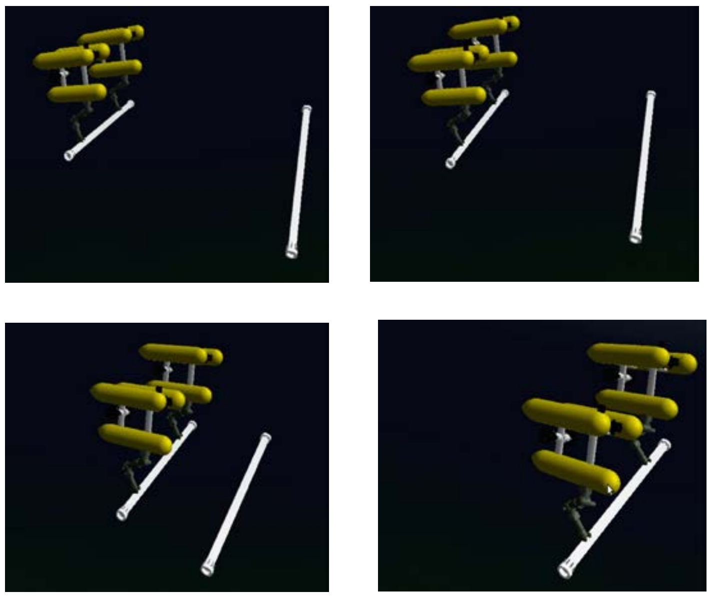

Fig. 6: Initial, intermediate, and final phases of a simulated cooperative transportation task

The image of Fig. 7 instead attempts to better evidencing the achievable dexterity in executing tasks of more preponderant manipulative nature than transportation.

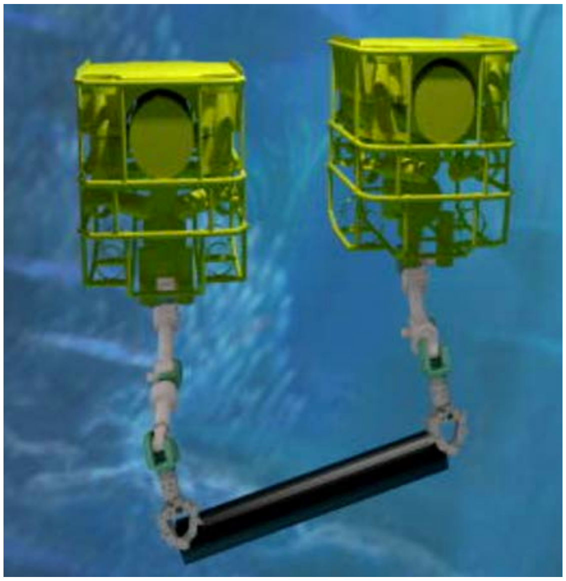

Fig. 7: A simulated cooperative object-manipulation task

Some video clips showing such simulated cooperative manipulation and transportation missions, also including the associated approach and final release phases, are available at the link (**LINK TBD)**

V CONCLUSIONS

The Italian national project MARIS is devoted to the integrated study and development of all methodologies and technologies that can enable the realization of agile autonomous robotized systems employable for intervention missions within underwater operative scenarios; even exhibiting cooperative capabilities. Such systems are in fact deemed having the non-negligible chance to become, for the future, progressively typical for many underwater, scarcely structured, applications of different types (underwater off-shore industry, sea floor mining, search-and-rescue operations, scientific missions, etc.); as by the way it can be confirmed by the existing different EU funded projects on the same subject, even if more focused on specific applications.

Within MARIS, also experimental proof-of-concept trials to be performed on prototype systems to be realized by the consortium, have been planned at the project start; which are now on the way to be completed by the cooperative experiments

The MARIS activities are conducted by a set of seven different research groups widely recognized as experts in very many of the aspects characterizing the underwater robotic field. Moreover, the preeminent presence in the consortium of different Departments members of ISME and CNR-ISSIA also guarantees an adequate support to the project, in terms of exploitation of the existing shared facilities, laboratories and equipment.

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