On Cooperation between Autonomous Underwater Floating Manipulation Systems

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Abstract— **This paper describes an unifying control framework which has been proposed and successfully employed within the recently concluded TRIDENT EU FP7 project. It further describes the extension of this proposed framework to dual arm free floating control case (single underwater vehicle with two 7 d.o.f redundant manipulators), and even the more challenging cooperative control of two I-AUVs for the transportation of large objects which is part of the currently ongoing Italian national project MARIS. The paper presents simulation results as well as actual experimental trials showing the effectiveness of this proposed control framework.**

I. Introduction

Research in the field of autonomous underwater robotics has come a long way both from a technological as well as from a theoretical point of view and can be dated back to the Amadeus project [2] in the late 90's until the recently concluded Trident project[1]. Carrying out complex operations like grasping, manipulation and transportation activities in harsh underwater environments are some of the greatest challenges that are being faced today. One of the major reasons which hinders the progress of such tasks are the severe conditions that exist in underwater scenarios. During the past few years, several accidents have occurred in the Atlantic Ocean which have very much contributed in evidencing the importance of having smart underwater robots, capable of executing interventions in an autonomous way. The factors mentioned above have led to a huge boost in the research carried out in the field of Intervention Autonomous Underwater Vehicles(I-AUV's) and has become a significant field of study in Robotics.

The work presented in this paper briefly describes the control methodology results achieved within the EU funded TRIDENT project [1] as well as the results obtained by extending this control methodology to the cases of dual arm free floating control and the cooperative control of two I-AUVS which derives its motivation from the currently ongoing Italian government funded project 'MARIS', whose aim is just to develop co-operative control policies of multiple I-AUV's devoted to manipulation and transportation of submerged large objects [13]. Within this context, the contribution of this paper is to give a brief overview of the development of control policies, within a unified framework, which help in accomplishing goals involved in the case of Trident[1], MARIS[13] as well as the case of dual arm free floating control. In case of MARIS, the cooperative control policy should rely on a minimal amount of information to be exchanged by the agents, due to the low acoustic bandwidth in underwater scenarios.

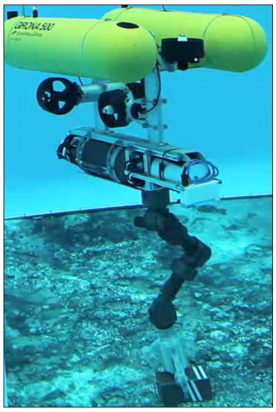


Fig. 1. The TRIDENT I-AUV system, encompassing the University of Girona G500 vehicle, the Graal Tech 7 d.o.f. underwater electrical arm and the University of Bologna dexterous hand (photo courtesy of the TRIDENT consortium)

To these aims, the paper is structured as follows. Section 2 briefly recalls the unifying framework for single agents [1], capable of handling equality and inequality objectives; while Section 3 will extend the approach to the case of dual arm free floating control along with preliminary simulation results. The successive section 4 will again extend this control framework to the mentioned decentralized multi objective constrained co-operative control problem. Finally, some conclusions will be discussed in section 5.

II. Task-Priority based Coordinated Control for Individual Floating Manipulation

The Trident project makes reference to a single free floating vehicle(6 d.o.f) that is endowed with a 7 d.o.f redundant manipulator as shown in Fig. 1. The system must be able to achieve its own multiple objectives of different nature. This may consist of achieving a given value of interest equal to a target value or maintaining this value of interest within a certain target set of values. The example of the first type can be the tool frame trying to exactly reach the goal frame, while some of the second type are for instance vehicle keeping the goal frame of the tool within its field of view of the camera, or maintaining its joint positions within certain bounds; or also guaranteeing its arm manipulability to be above a given threshold.

For individually operating systems, a task-priority based framework [3], can be adopted where each task can be assigned a priority according to its importance; and where the various tasks are therefore solved according to their priority in a descending order, meaning that the highest priority task is solved first and then the solutions of the other tasks are solved inside the kernel subspace of the higher priority ones. The task priority paradigm has been implemented in various fields of robotics:mobile manipulators such as [8], [9]; multiple coordinated mobile manipulators [10] as well as in humanoid robots [11],[12].

However one of the limitations of the original task priority framework was that only equality objectives were considered. Hence in order to also solve for inequality objectives an extension of the original task priority based framework has been therefore developed in [1] [4], via the suitable use of activation functions which are used for smoothly activating and de-activating tasks, when inequality conditions are achieved or nearly to be achieved. An important advantage of this method is that, when a task disappears from the priority list it results in an enlargement of the mobility space which in turn is favorable to the lower priority tasks.

A. *Individual Control Objectives*

This subsection gives the list of the objectives(equality as well as inequality) that are normally required for individually operating systems in the order of their priority(first task with the highest priority and so on).
1) Joint Limits: This is an inequality type task used to maintain the joints within well defined bounds in order to maintain safety and good operability of the arm.
2) Manipulability: In order to guarantee the arm operating with a good dexterity, the arm itself must also keep its manipulability measure [5] above a minimum value, thus leading to th0e following inequality type objective.
3) Horizontal Attitude: The vehicle should stay at an almost horizontal attitude established by bounds on its pitch angle.
4) Camera centering for object transportation: This objective is activated during the transportation phase, and requires the goal frame grossly maintained within the visual cone of the endowed forward-looking camera.
5) Camera centering for object positioning: This task is activated during the final positioning phase and requires the grasped object frame and the goal one both maintained in the field of view of the endowing positioning camera.
6) Positioning camera distance and height: This objective is activated during the positioning phase and requires the positioning camera to be above a certain height and below a certain horizontal distance from the goal frame; in order to enable the best operability conditions for the positioning camera.
7) Grasped object positioning: This objective is active during both the transportation and final positioning phase. It requires the grasped object frame approaching the goal one, still to be exactly positioned on it.
8) Vehicle motion minimality: Since the vehicle generally exhibits a larger mass and inertia than the arm, during the final positioning phase it is advisable to have it move, only the strict necessary amount needed for accomplishing the related tasks. Thus always favoring the use of the arm whenever possible,in any situation, depending on the task status(active or not active).

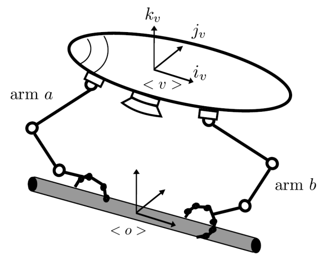


Fig. 2. Dual arm configuration with the relevant frames

The mathematical details regarding the fundamental algorithmic structure used in the Trident project and managing the high priority, low priority equality, inequality tasks has been extensively discussed in [1]. The experimental trials performed in the European project Trident have also been extensively detailed in [1].

III. Extension to Dual Arm Free Floating Case

Consider the system shown in the Fig. 2, where the vehicle is endowed with two redundant 7 d.o.f manipulators. Here it is assumed that two vehicles have separately grasped a common object. The objective of this mission is to transport the object to a desired goal position. To this aim, the whole system must be coordinated in a suitable way to comply with the kinematic constraints that is imposed by the object itself, i.e

$$J^a \dot{q}^a + Sv = J^b \dot{q}^b + Sv, \tag{1}$$

where J^a is the Jacobian of the arm a transferred to an object frame $< o >$, J^b is the Jacobian of the arm b, transferred to the same object frame $< o >$. Finally, S is the rigid body transformation matrix which reports the vehicle velocity on the object frame. As far as the vehicle is concerned, it only adds rigid body movements to the grasped object;thereby not creating any problems related to the kinematic constraints. Thus the kinematic constraint can be further simplified to

$$J^a \dot{q}^a = J^b \dot{q}^b. \tag{2}$$

One of the most simple ways to deal with this kind of situation is by considering the following equality constraint

$$\begin{bmatrix} J^a & -J^b \end{bmatrix} \begin{bmatrix} \dot{q}^a \\ \dot{q}^b \end{bmatrix} \triangleq \hat{J}\dot{q} = 0 \tag{3}$$

which should clearly take the highest priority. Therefore, the corresponding task would be

$$\mathcal{S}_1 \triangleq \left\{ \dot{q} = \arg\min_{\dot{q}} \left\| \hat{J}\dot{q} \right\|^2 \right\}, \tag{4}$$

whose solution is very simple and results to be

$$\dot{q} = \rho_1 + Q_1 z_1 = 0 + (I - \hat{J}^{\#}\hat{J}) z_1 \;\; ; \;\; \forall z_1. \tag{5}$$

All the subsequent tasks will have to be carried out by exploiting the residual arbitrariness represented by z_1[1], which is the sole one that respects the kinematic constraint.

Then, the remaining inequality objectives, such as joint limits and manipulability, can be solved for both arms. For example, the first inequality constraint would lead to

$$\mathcal{S}_2 \triangleq \left\{ \dot{q} = Q_1 z_1 : z_1 = \arg\min_{z_1} \left\| A_2 \Sigma_2 - \hat{G}_2 z_1 \right\|^2 \right\}, \quad (6)$$

where we have preliminarily let

$$A_2 \triangleq \begin{bmatrix} \alpha_2^a & 0 \\ 0 & \alpha_2^b \end{bmatrix} ; \hat{G}_2 \triangleq A_2 \begin{bmatrix} {n_2^a}^T H_2^a & 0 \\ 0 & {n_2^b}^T H_2^b \end{bmatrix} Q_1, \quad (7)$$

and where Σ_2 is the stacked vector of the two references σ_2^a and σ_2^b.

The matrix Q_1 forces the solution of the inequality tasks to respect the first equality constraint which corresponds to the kinematic constraint. The procedure can be repeated as in the single arm case, with the only difference that now we are considering the vector $\dot{q}$ as the stacked vector of all the joint variables for both arms, and each task is represented by a Jacobian matrix which is a diagonal matrix of the relevant Jacobians of the two arms for the specific task. Naturally, the same holds for the vehicle level.

It can clearly seen that dual arm free floating case gives rise to multidimensional inequality tasks. This problem of solving multidimensional inequality tasks has been resolved in [4] by introducing a novel regularization function called task based regularization.

A. *Simulation Results for Dual Arm Free Floating Case*

This subsection gives details about the simulation results obtained by considering an underwater vehicle, endowed with two 7 d.o.f redundant manipulators whose ultimate goal is to transport the object from an initial position to a final goal position assuming that the object is grasped. The system therefore has to accomplish the following objectives;minimizing the interaction forces on the object, keeping away from the joint limits, keeping the manipulability measure above a certain threshold and maintaining the horizontal attitude of the vehicle. Figures 3(a), 3(b) and 3(c) shows how the arm and the vehicle requested velocities are continous. The successive figures 4(a), 4(b) shows the time history of the activation functions, showing how the tasks are activated and deactivated during different stages of the trial. Fig 4(c) shows the error in the final positioning of the object which is zero, showing the effectiveness of this proposed control framework. UWsim [7] which is an underwater robotics simulator was used for performing visual rendering. Fig 5 shows that the system manages to successfully accomplish the objective by transporting the object to its goal position.

IV. Extension to Cooperatively Operating Underwater Floating Manipulators

This section makes reference to the MARIS project [13] where the goal is to develop cooperative control policies of multiple I-AUVs devoted to the manipulation and transportation of large objects in underwater environments, within a unified framework. Consider the Fig. 6 which shows two underwater vehicles(6 d.o.f each), each one endowing a 7 d.o.f manipulator. The work presented below can be seen as an extension of control methodology results achieved within the EU funded TRIDENT project [1]. Firstly, we will describe the prioritized control law for individual floating manipulation systems [14] and then extend it to cooperatively operating underwater floating manipulators.

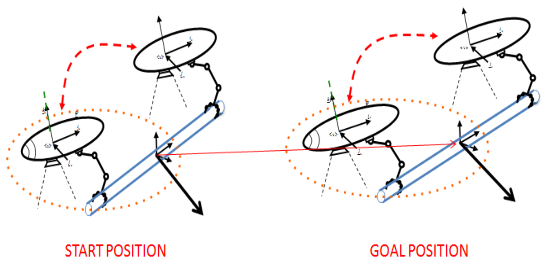


Fig. 6. Transportation and Positioning Phase

A. *Prioritized Control law for individual floating manipulation systems*

Consider the absolute velocity exhibited by the tool-frame $< t >$ (i.e.the grasped object frame), each one assumed with components on $< t >$ itself, which can be expressed as:

$$\dot{x} = J\dot{q} + Sv \doteq H\dot{y} \quad (8)$$

where $\dot{q}$ represents the arm joint velocity, v represent the vehicle velocity, each one with components on frame $< t >$; while matrices J and S respectively represent the arm and vehicle Jacobian matrices projected on frame $< t >$; with the second one (i.e matrix S) simply corresponding to the existing non-singular rigid body velocity transformation from frame $< v >$ to frame $< t >$, at the current arm posture. Now assuming that the vehicle is fully actuated $\dot{x}$ can consequently span the entire 6-dimensional space. Therefore instead of the system velocity couple $(\dot{q}, v)$ also the couple $(\dot{q}, \dot{x})$ can be assumed as representative of the overall system motion; in the sense that a one-to-one relationship is immediately established between the two via the non-singular inverse formula:

$$v = S^{-1}\dot{x} - S^{-1}J\dot{q} \quad (9)$$

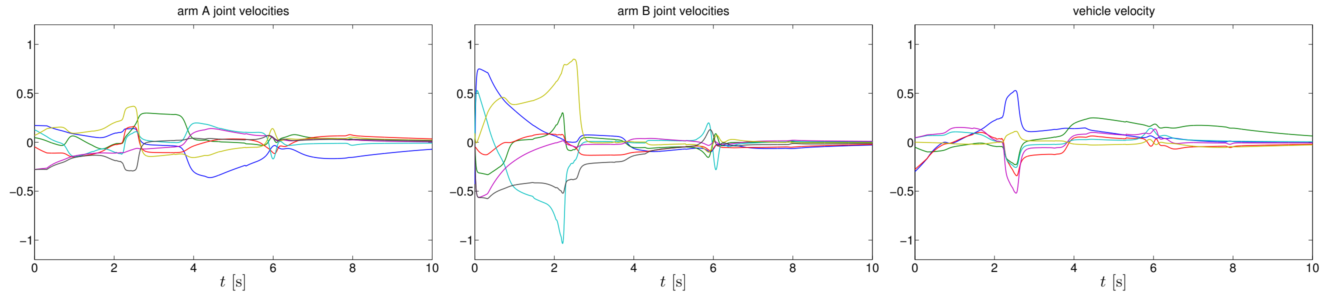
which leads to the following one-to-one relationship:

$$\dot{y} = \begin{bmatrix} 0 \\ S_a^{-1} \end{bmatrix} \dot{x} + \begin{bmatrix} I \\ -S_a^{-1}J \end{bmatrix} \dot{q} \doteq M\dot{x} + Q\dot{q} \quad (10)$$

With reference to the introduced inverse relationship, but without altering it's fundamental structure, the prioritized control law develops, at each time instant, via the execution of the following two sequential algorithmic runs:

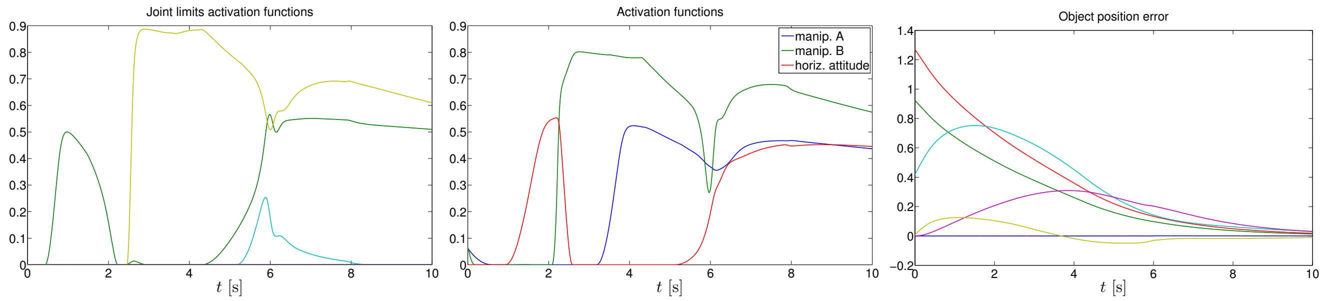
a) First run (Tool-frame velocity conditioning): Here the sequence of prioritized tasks are optimized with respect to arm joint velocities by using the same structure of [1], [4](tool frame velocity vector assigned as dummy vector parameter). This will formerly lead to the following conditionally optimal linear control law:

$$\dot{q} = \dot{\rho} + P\dot{x} \quad (11)$$



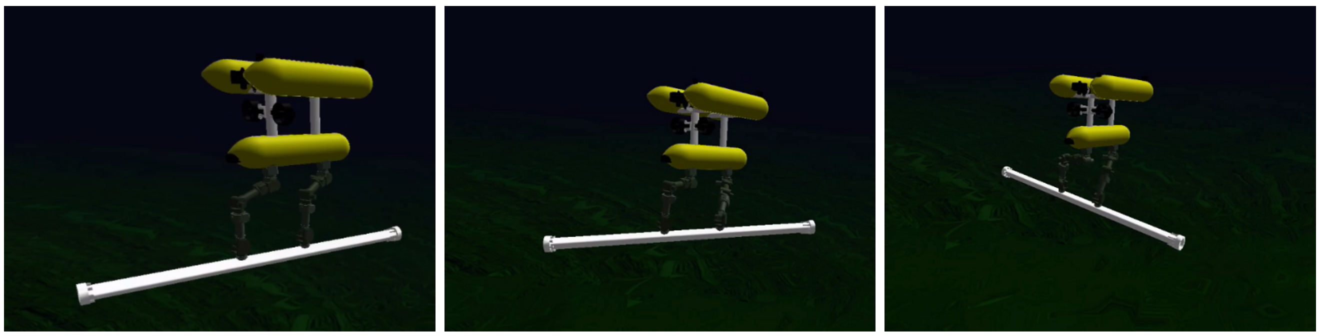
(a) (b) (c)

Fig. 3. Dual arm simulation: (a) arm A joint velocities, (b) arm B joint velocities (c) vehicle velocity.



(a) (b) (c)

Fig. 4. Dual arm simulation: (a) activation functions for the joint limits task, (b) activation functions for the other tasks (c) object position error.



(a) (b) (c)

Fig. 5. Dual arm simulation: Different Stages in the Transportation Phase using UWsim

Where $\dot{\rho}$ is the conditionally optimal joint velocity reference for a null tool-frame velocity conditioning; while the additional term P$\dot{x}$ leads to conditional optimality for any non-zero tool-frame velocity parametrization.
b) Second run (Tool-frame velocity optimization): With the joint velocity vector $\dot{q}$ constrained to obey to the above control law, the sequence of prioritized tasks is then optimized with respect to the tool-frame velocity vector parameter $\dot{x}$ by still using the same algorithmic structure of [1], [4]; thus finally leading to the following globally optimal joint velocity control action:

$$\dot{\bar{q}} = \dot{\rho} + P\dot{\bar{x}} \tag{12}$$

where $\dot{\bar{x}}$ is the optimal value for the tool-frame velocity vector parameter. Note that, accordingly with the above optimal control action, the optimal vehicle velocity is consequently assigned as:

$$\dot{\bar{v}} = S^{-1}\dot{\bar{x}} - S^{-1}J\dot{\bar{q}} \tag{13}$$

This together along with above estabilished control law in (12) leads to the optimal system velocity vector $\dot{\bar{y}}$ given by:

$$\dot{\bar{y}} = M\dot{\bar{x}} + Q\dot{\bar{q}} \tag{14}$$

B. Prioritized Control laws for cooperatively operating floating manipulation systems

The section presents a novel cooperative control policy that has been developed which exchanges just six numbers (the evaluated tool frame velocities) at each time step, while still being able to achieve all the goals with extremely good performances, in spite of the imposed limitations to the information exchange. To this aim, two separate KCL's are designed for each system. At each sampling interval, each

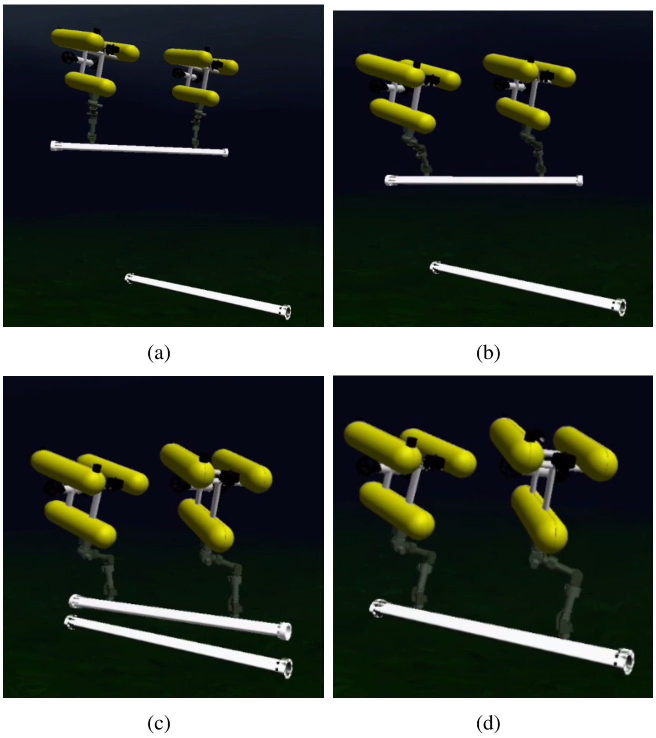


Fig. 7. Different stages in the transportation and positioning phase

system performs its global optimization procedure as if they were the sole ones acting on the grasped object; thus leading to a couple of optimal joint and vehicle velocity control laws. After this, and during the same sampling interval, the individually optimal tool frames velocities (6 numbers) are exchanged and a common tool frame velocity value is then obtained from this exchange. Then within the same sampling interval, each system simultaneously re-tunes its joint and vehicle velocity references conditioned to this common tool frame velocity value; thus providing conditionally optimal system velocity references. The mathematical details and the structure of the prioritized control laws have been extensively detailed in [14].

C. Preliminary Simulation Results

Two underwater vehicles(6 d.o.f each), each endowed with a 7 d.o.f manipulator have to transport an object from an initial position to a final goal position assuming that the object is already grasped. In order to achieve this objective the following tasks have been considered: keeping away from the joint limits, maintaining the manipulability value above a certain threshold, maintaining the horizontal attitude of the vehicles, keeping a fixed distance between the two vehicles to avoid collisions and minimizing the vehicle motion[14]. The two systems are commanded to transport the object to the goal position(8,5,1) meters rotated by an anlge of 30 degrees along the X axis. Fig. 7 shows he visual rendering carried out by using UWsim[7]. The details regarding the activation functions, vehicle and arm joint velocities have been explained clearly in [14].

V. Conclusion

In this paper we have successfully presented a unifying control framework which has been used for individual floating manipulation systems, and has been further extended to work with cooperatively operating underwater floating manipulators as well as the case of dual arm free floating control. The main features are the simplicity and the ease with which this control framework can be extended for the cases of dual arm free floating control and cooperatively operating underwater floating manipulators. Thus without altering the fundamental structure of the framework, it can be easily adapted to work for more complex problems as described in the paper.

VI. Acknowledgments

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References

[1] Simetti, E., Casalino, G., Torelli, S., Sperinde A. and Turetta,A. (2014), Floating Underwater Manipulation: Developed Control Methodology and Experimental Validation within the TRIDENT Project. Journal of Field Robotics, volume 31(3):364385, May 2014.

[2] Lane, D. M., Davies, J. B. C., Casalino, G., Bartolini, G., Cannata, G., Veruggio, G., Canals, M., Smith, C., O'Brien, D. J., Pickett, M., Robinson, G., Jones, D., Scott, E., Ferrara, A., Angelleti, D., Coccoli, M., Bono, R., Virgili, P., Pallas, R., and Gracia, E. (1997). Amadeus: advanced manipulation for deep underwater sampling. IEEE Robot Autom Mag, 4(4):34-45.

[3] Siciliano, B. and Slotine, J.-J. E. (1991). A general framework for managing multiple tasks in highly redundant robotic systems. In Proc. Fifth Int Advanced Robotics 'Robots in Unstructured Environments', 91 ICAR. Conf, pages 1211-1216.

[4] Simetti, E. and Casalino, G. Integrating Inequality Constraints and Task Transitions in Priority Based Control. International Conference on Robotics and Automation (ICRA 2015). submitted.

[5] Yoshikawa, T. (1985). Manipulability of robotic mechanisms. Int. J. of Robotics Research, 4(1):3-9.

[6] Oleari, F. and Kallasi, F. and Lodi Rizzini, D. and Aleotti, J. and Caselli, S. Performance Evaluation of a Low-Cost Stereo Vision System for Underwater Object Detection. Proc. of the World Congr. of the International Federation of Automatic Control (IFAC), 2014, pages 3388-3394.

[7] Prats, M.; Perez, J.; Fernandez, J.J.; Sanz, P.J., "An open source tool for simulation and supervision of underwater intervention missions", 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 2577-2582, 7-12 Oct. 2012.

[8] Antonelli, G. and Chiaverini, S. (1998). Task-priority redundancy resolution for underwater vehicle-manipulator systems. In Proc. IEEE International Conference on Robotics and Automation, volume 1,pages 768-773.

[9] Antonelli, G. and Chiaverini, S. (2003). Fuzzy redundancy resolution and motion coordination for underwater vehicle-manipulator systems. IEEE Trans. on Fuzzy Systems, 11(1):109-120.

[10] Padir, T. (2005). Kinematic redundancy resolution for two cooperating underwater vehicles with on-board manipulators. In Proc. IEEE Int Systems, Man and Cybernetics Conf, volume 4, pages 3137-3142.

[11] Sentis, L. and Khatib, O. (2005). Control of free-floating humanoid robots through task prioritization. In Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain.

[12] Sugiura, H., Gienger, M., Janssen, H., and Goerick, C. (2007). Real-time collision avoidance with whole body motion control for humanoid robots. In Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems IROS 2007, pages 2053-2058.
[13] Casalino, G., Caccia, M., Caiti, A., Antonelli, G., Indiveri, G., Melchiorri, C., and Caselli,S.: MARIS: A National Project on Marine Robotics for InterventionS. 22nd Mediterranean Conference of Control and Automation (MED),page:864 - 869,(June 2014).
[14] Manerikar, N., Simetti, E., Casalino, G., Torelli, S., and Sperinde, A. On Autonomous Cooperative Underwater Floating Manipulation Systems. International Conference on Robotics and Automation (ICRA 2015). submitted.