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On Autonomous Cooperative Underwater Floating Manipulation Systems*

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***Abstract*— In this paper we present a novel co-operative control policy purely for the transportation of large objects in underwater environments using two free floating vehicles, each one endowed with a 7 d.o.f redundant manipulator. Due to the presence of harsh conditions in underwater scenarios, it is extremely important to realize algorithms that depend on a minimal amount of explicit information exchanged by the agent, or without any exchange of information at all. To achieve this goal the control policy proposed in the paper only requires the exchange of six numbers at each time instant, while however exhibiting extremely good performances, inspite of the restraints on the information exchange.**

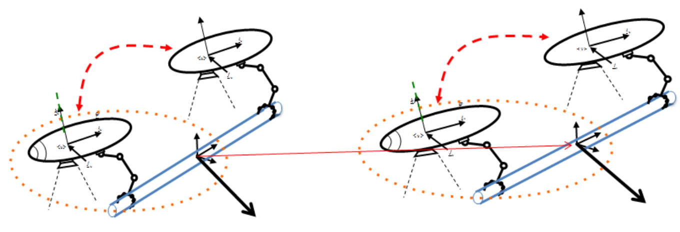

Fig. 1. Transportation and Positioning Phase

I. INTRODUCTION

There has been a tremendous progress in the field of autonomous underwater robotics both from a technological point of view as well as from a theoritical point of view which can be dated back to the Amadeus project in the late 90's until the recently concluded Trident project. Some of the biggest challenges faced in underwater robotics have been the operations like grasping, manipulations and transportation activites; as well as assembly/disassembly ones. The difficulties in performing these tasks are mainly related to the severe conditions that exist in underwater enviroments. During the past few years, several accidents have occured 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 can be seen as an extension of control methodology results achieved within the EU funded TRIDENT project [1] and 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. Within this context, the contribution of this paper is the development, within a unified framework, of a cooperative control policy relevant to both the involved mission phases i.e transportation, then followed by the final positioning of the shared object grasped by two agents, as shown in Fig. 1. Moreover, such cooperative control policy must rely on a minimal amount of information to be exchanged at each step by the agents, because of the low acoustic bandwidth available in underwater environments.
To these aims, the paper is structured as follows. Section 2 briefly recalls the already unifying framework for single agents [1], capable of handling equality and inequality objectives; while Section 3 will extend the approach to the mentioned decentralized multi objective constrained cooperative control problem. Simulation results supporting the proposed approach will be then presented in section 4. Finally, some conclusions and future works will be discussed in section 5.

II. TASK-PRIORITY BASED COORDINATED CONTROL FOR INDIVIDUAL FLOATING MANIPULATION

The MARIS project makes reference to two free floating vehicles (6 d.o.f. each), each one endowing a 7 d.o.f redundant manipulator. Individually, each system must achieve their 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

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various fields of robotics:mobile manipulators such as [7], [8]; multiple coordinated mobile manipulators [9] as well as in humanoid robots [10],[11].

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], 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

Given below are the set of objectives (equality as well as inequality) listed in the order of their priority (first task with highest priority and so on) that generally need to be considered for an individually operating system.
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 [4] 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).
The mathematical details of managing the high priority, low priority equality and inequality tasks has been extensively discussed in [1].

B. Algorithmic structure of the prioritized control law

Consider the absolute velocity exhibited by the tool-frame $< t >$ (i.e.the grasped object frame), represented by the stacked vector of its linear and angular absolute velocities, each one assumed with components on $< t >$ itself, which can be expressed as:

$$\dot{x} = J\dot{q} + Sv \doteq H\dot{y} \tag{1}$$

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. Moreover the stacking of vectors $\dot{q}$ and v into vector $\dot{y}$ represents the system-velocity vector, directly related with $\dot{x}$ via the resulting overall tool-frame Jacobian matrix $H \doteq [J, S]$. By now assuming a fully actuated vehicle (i.e. exhibiting $v \in R^6$) we can then see how, under this sole assumption, $\dot{x}$ 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:

$$v = S^{-1}\dot{x} - S^{-1}J\dot{q} \tag{2}$$

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

$$\dot{y} = \begin{bmatrix} 0 \\ S_a^{-1} \end{bmatrix} \dot{x} + \begin{bmatrix} I \\ -S_a^{-1}J \end{bmatrix} \dot{q} \doteq M\dot{x} + Q\dot{q} \tag{3}$$

The reference here made to the above inverted relationship (3), instead than the direct one, actually constitutes the sole difference with respect to what has been already developed in [1]. Thus, this slight modification without altering the fundamental structure of the already developed prioritized control law for individual underwater floating manipulators, will instead prove to be very useful when such individual control laws will have to be integrated within a cooperative environment, involving more than a single agent. 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): With the tool-frame velocity vector assigned as a dummy vector parameter, the sequence of prioritized tasks is optimized with respect to the arm joint velocities by using the same algorithmic structure of [1]; thus formerly leading to the following conditionally optimal linear control law:

$$\dot{q} = \dot{\rho} + P\dot{x} \tag{4}$$

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]; thus finally leading to the following globally optimal joint velocity control action:

$$\dot{\bar{q}} = \dot{\rho} + P\dot{\bar{x}} \tag{5}$$

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:

$$\dot{\bar{v}} = S^{-1}\dot{\bar{x}} - S^{-1}J\dot{\bar{q}} \tag{6}$$

This together along with above estabilished control law in (5) leads to the optimal system velocity vector $\dot{\bar{y}}$ given by:

$$\dot{\bar{y}} = M\dot{\bar{x}} + Q\dot{\bar{q}} \tag{7}$$

III. Extension to cooperatively operating underwater floating manipulators

Once the two floating manipulators have firmly grasped a shared object, as indicated in Fig.1, the problem of transporting the object, and finally positioning its attached frame $< t >$ on the goal frame $< g >$, has to be now solved within the set of system velocities $\dot{y}_a$, $\dot{y}_b$ characterized by the following parametrization:

$$\dot{y}_a = M_a\dot{x} + Q\dot{q}_a \tag{8}$$
$$\dot{y}_b = M_b\dot{x} + Q\dot{q}_b \tag{9}$$

with a common arbitrary tool-frame velocity $\dot{x}$ and separately arbitrary joint velocity vectors $\dot{q}_a$ and $\dot{q}_b$.

In the cooperative scenario, an additional task of maintaining a given distance between the two vehicles will be introduced in order to avoid collisions. The cooperative control problem might actually be optimally solved by simply extending the application of previously outlined task priority based individual control law in the following way:

a) Independent first runs (Separate tool-frame velocity conditioning): At each time instant each system independently determines its own conditionally optimal joint velocity control law, by optimizing its own list of prioritized tasks as if it were the sole agent acting on the object; thus separately obtaining (i.e. in a fully decentralized way) the following couple of separate optimal joint velocity control laws:

$$\dot{q}_a = \dot{\rho}_a + P_a\dot{x}_a \tag{10}$$
$$\dot{q}_b = \dot{\rho}_b + P_b\dot{x}_b \tag{11}$$

With $\dot{\rho}_a$, $\dot{\rho}_b$ representing the corresponding tool-frame velocity dummy parametrization for each system.

b) Global second run (Tool-frame velocity optimization): By setting the common parametrization $\dot{x}_a \doteq \dot{x}_b \doteq \dot{x}$, the second optimization run for a common $\dot{x}$ should be now performed on a global basis by merging the separate lists of tasks into a whole superset of tasks (allowing a complete exchange of information which must include the task lists, the above devised conditioned control laws, as well as the configuration state of each system and all relevant Jacobian matrices). This would consequently lead to the optimal common tool frame velocity $\dot{x}^\circ$, that would consequently establish the associated optimal joint velocity control laws:

$$\dot{q}_a^\circ = \dot{\rho}_a + P_a\dot{x}^\circ \tag{12}$$
$$\dot{q}_b^\circ = \dot{\rho}_b + P_b\dot{x}^\circ \tag{13}$$

In turn each one leading to the corresponding optimal vehicle velocities v_a°, v_b° via (2) given by:

$$v_a^\circ = -S_a^{-1}\dot{x}^\circ - S_a^{-1}J_a\dot{q}_a^\circ \tag{14}$$
$$v_b^\circ = -S_b^{-1}\dot{x}^\circ - S_b^{-1}J_b\dot{q}_b^\circ \tag{15}$$

Consequently the optimal system velocities $\dot{y}_a^\circ$, $\dot{y}_b^\circ$ are obtained via (8) and (9) given by:

$$\dot{y}_a^\circ = M_a\dot{x}^\circ + Q_a\dot{q}_a^\circ \tag{16}$$
$$\dot{y}_b^\circ = M_b\dot{x}^\circ + Q_b\dot{q}_b^\circ \tag{17}$$

Since the above outlined global second run would actually require an excessive amount of data exchange between the agents, it generally turns out to be practically unfeasible, especially within the case considered here of underwater interventions, where low-bandwidth acoustic communication channels typically are the sole available means for data exchanges. As a consequence of the above consideration, clearly forcing us to renounce the global optimality, the following suboptimal procedure, however based on a reduced amount of information to be exchanged, can be therefore proposed:

a) Independent first and second runs (Separate optimizations): At each time instant each system independently performs its own global optimization, as if it were the sole agent acting on the grasped object; thus formerly obtaining the following couple of individually optimal joint velocity control laws:

$$\dot{\bar{q}}_a = \dot{\rho}_a + P_a\dot{\bar{x}}_a \tag{18}$$
$$\dot{\bar{q}}_b = \dot{\rho}_b + P_b\dot{\bar{x}}_b \tag{19}$$

b) Tool frame velocities exchange and fusion policy: At each time instant the separately evaluated individually optimal tool-frame velocities $\dot{\bar{x}}_a$, $\dot{\bar{x}}_b$ are exchanged (this requires the transmission of solely six numbers in both directions) and a common value $\dot{\hat{x}}$ is determined as the result of an a-priori agreed fusion policy. Quite simply such fusion policy may trivially be the mean value between $\dot{\bar{x}}_a$, $\dot{\bar{x}}_b$ or more generally a suitable convex combination of them; or even more sophisticated fusion policies whose devising is however still the subject of further investigations. In a broader sense, it should be noted that such convex combinations could be used where one system can be the leader and the other system can be the follower and they can even smoothly change the role depending on the scenario.

c) Joint velocities retuning: At each time instant each system simply retunes, via trivial substitution into equations (10) and (11), its joint velocity references to the so established conditioning common tool-frame velocity value, thus obtaining the following couple of separate conditionally optimal joint velocity control laws:

$$\dot{\hat{q}}_a = \dot{\rho}_a + P_a \dot{\hat{x}} \tag{20}$$

$$\dot{\hat{q}}_b = \dot{\rho}_b + P_b \dot{\hat{x}} \tag{21}$$

Each one characterized by the common tool-frame velocity vector $\dot{\hat{x}}$. The above equations are then used for setting the corresponding conditionally optimal vehicle velocities $\hat{v}_a$, $\hat{v}_b$ given by:

$$\hat{v}_a = -S_a^{-1} \dot{\hat{x}} - S_a^{-1} J_a \dot{\hat{q}}_a \tag{22}$$

$$\hat{v}_b = -S_b^{-1} \dot{\hat{x}} - S_b^{-1} J_b \dot{\hat{q}}_b \tag{23}$$

Then the conditionally optimal system velocities $\dot{\hat{y}}_a, \dot{\hat{y}}_b$ are computed via equation (8) and (9) which leads to:

$$\dot{\hat{y}}_a = M_a \dot{\hat{x}} + \hat{Q}_a \dot{\hat{q}}_a \tag{24}$$

$$\dot{\hat{y}}_b = M_b \dot{\hat{x}} + \hat{Q}_b \dot{\hat{q}}_b \tag{25}$$

The main idea behind proposing the above solution, is not only to estabilish a common tool-frame velocity (as required by the firm grasping constraints) but also to resort to the common tool-frame velocity which may be considered as reasonable compromise between two individual optimal values; in any case without requiring any unfeasible amount of information exchange between the agents.
As a matter of fact, further investigations are actually needed for measuring the degree of sub-optimality introduced by the employment of $\dot{\hat{x}}$ in lieu of the optimal one $\dot{x}^{\circ}$, which however remains (though almost impossible to be evaluated within underwater environment) a reference stone with respect to which any suboptimal control law has to be compared.
Moreover the possible existence of secondary effects if any, that might appear as a consequence of the introduced sub-optimality, are still to be investigated. However, the extensive simulations performed in the next section show encouraging results even after exchanging just the mean($\dot{\hat{x}}$) between $\dot{\bar{x}}_a$, $\dot{\bar{x}}_b$.

IV. Preliminary Simulation Results

In this section simulation results will be presented by using the algorithms that have been discussed in the sections above. Two free-floating vehicles (6 d.o.f) endowed with two redundant manipulators (7 d.o.f) must transport an object from an initial starting position to a final position assuming that object is grasped. Therefore the main task is thus transportation, followed by proper positioning of the object. The tasks are in order of priority: keeping away from joint limits, keeping the manipulability measure above a certain threshold, maintaining the horizontal attitude of the vehicles, maintaining a fixed distance between the vehicles, reaching the desired goal position and minimizing the vehicle velocity. The tasks related to the camera have not been included in these preliminary simulations and will be added in the future.

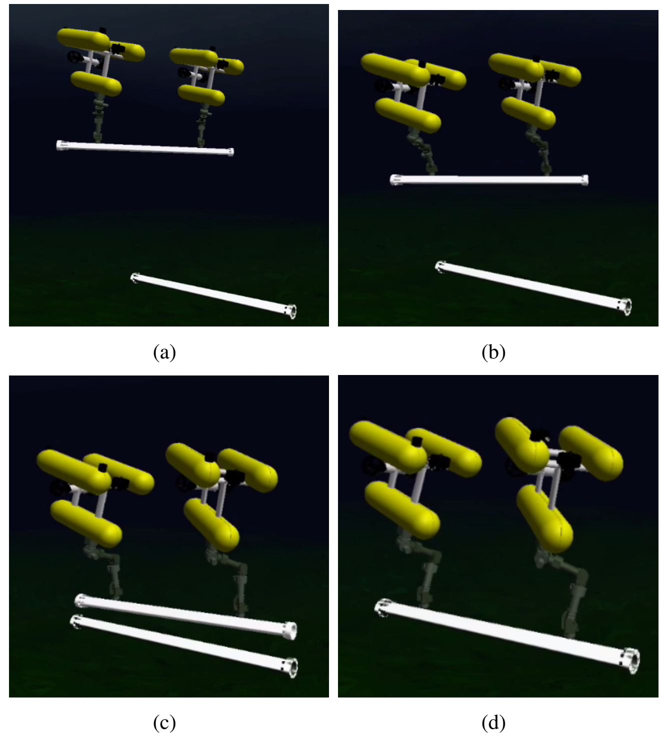

Fig. 2. Different stages in the transportation and positioning phase

The two systems are commanded to transport the object 8meters along the x-axis, 1meter along the y-axis and 5meters along the z-axis. Therefore goal position of the object in xyz co-ordinates is (8,5,1) meters rotated by an angle of 30 degrees around the x-axis. UWSim[6] which is an underwater robotics simulator will be used for performing visual rendering.
The precise values of the parameters for the various tasks like joint limits, manipulability have been given in the table below:

Fig. 4 reports the time history of the activation functions for the joint limits, manipulability, horizontal attitude and distance between the vehicles tasks for the systems A and B. From figures 4(a), 4(b), 4(c), 4(d) it can be seen that different tasks are in transition during the trial simulations. The proposed framework allows to maintain the corresponding variable of each task within its given boundaries using suitable smooth activation functions for activating and deactivating the tasks[1]. With this approach, the system manages to successfully accomplish the final objective of the mission, by transporting the object to the desired goal position as seen from the Fig. 2. Fig. 5 shows the error in the final positioning of the object which is zero, showing the effectiveness of this approach. The arm joint velocities and the vehicle velocities obtained during simulation for system A and system B in Fig. 3 shows the smoothness of the control that has been achieved.

V. Conclusion and Future Works

In this paper a novel algorithm has been presented for autonomous co-operative transportation of large objects by

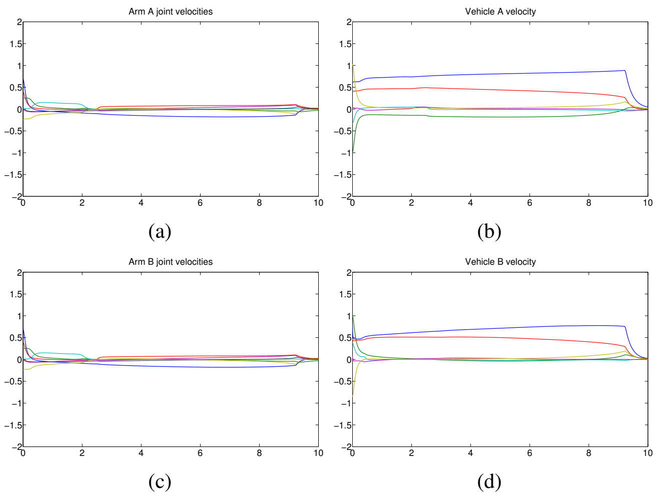

Fig. 3. Arm joint velocities and vehicle velocities of System A and B

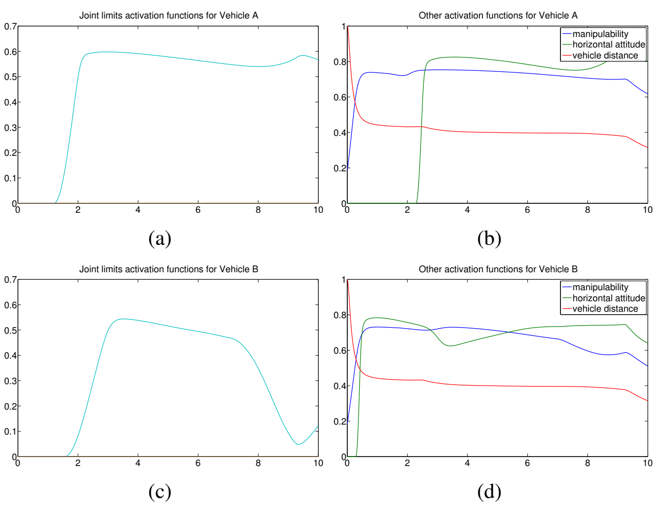

Fig. 4. Activation functions for System A and B

two free floating vehicles mounted with redundant manipulators. The novelty of the algorithm consists in the mimimum amount of information exchange (6 numbers in this case) that is needed in successfully accomplishing the desired objectives. The further step is to develop the underlying dynamics. Once the theoritical foundations have been developed also for the dynamics and verified by carrying out simulations, actual experimental trials will be performed later this year. Also one of the major challenges is to completely eliminate the exchange of information between the two agents by obtaining information about the interaction forces and object stresses using force torque sensors mounted on the wrist of the two manipulators. The future works also include resolving issues of multi rate sampling since the arm and vehicle work at different control frequencies and also the compensation of disturbances.

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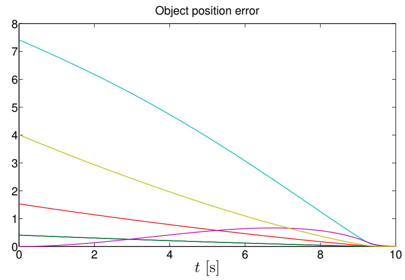

Fig. 5. Error in Positioning of the object

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