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Underwater Floating Manipulation for Robotic Interventions ⋆

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Abstract: The paper introduces the control and coordination problems encountered within the employment of autonomous underwater floating manipulators for object retrieval from the sea floor. To this respect, the employment of unifying control framework, capable of guaranteeing the necessary system agility and flexibility, is outlined. Some experimental results from the TRIDENT FP7 project are presented, along with the possible extension of the proposed framework to the case of dual arm manipulators.

Keywords: task priority control; underwater floating manipulation; autonomous vehicles; redundant manipulators; redundancy control; cooperative control

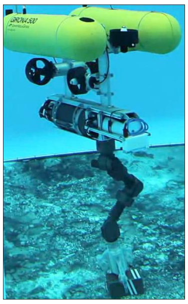

Fig. 1. The TRIDENT I-AUV system, encompassing the University of Girona G500 vehicle, the Graal Tech 7 d.o.f. underwater electrical arm and the University of Bologna dexterous hand (photo courtesy of the TRIDENT consortium)

1. INTRODUCTION

An automated system for underwater intervention is here intended as an autonomous underwater floating manipulator capable of collecting objects corresponding to an a-priori assigned template. Fig. 1 outlines the most recent realization of a system of this kind (completed in 2012 within the EU-funded project TRIDENT Sanz et al. (2012)), which is characterized by a vehicle with an endowed 7-dof arm exhibiting comparable masses and inertia. This results in a potentially faster and more agile platform than the few previous realizations of I-AUVs (Intervention Autonomous Underwater Vehicle, see Antonelli (2014) for a complete review of the subject), which were usually characterized by having heavy vehicles compared to the endowed arms.

The main capabilities of such systems mainly consist in exploring an assigned area of the sea floor, until an object corresponding to the assigned template is recognized and then recovering it from the sea floor. The first capability reenters within the topics of navigation, patrolling, visual mapping, etc., which are typical of traditional AUVs and consequently will not be discussed here. Only the second capability will be discussed, since most distinctive of the considered I-AUV system.

Focusing on the object grasping problem, note that aside from the ultimate recovering objective, which translates into a position control for the end-effector, also other ones must be simultaneously considered. To cite a few examples, the arm's joint limits must be respected, and the arm singular postures avoided. Moreover, the object must be grossly centered inside the stereo camera visual cone and within certain horizontal and vertical distance bounds from the camera frame, otherwise the visual feedback would be lost. Furthermore, the vehicle tilt angles should be kept within security bounds.

With the exception of the position control of the end-effector, which is clearly an equality condition to be achieved, all the other control objectives are represented by scalar inequality conditions involving different system variables, to be achieved for assuring the system safety and/or its operational-enabling conditions. As a consequence, the achievement of the inequality conditions deserves a priority higher than the one regarding the grasping task. Further, such a prioritized behavior should be obtained in a concurrent way (i.e. avoiding sequential motions), which means that each task can only exploit the residual system mobility allowed by the contemporary progress of its higher priority tasks.

In this way, the available mobility will progressively increase during time, following with the progressive achieve-

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ment of all inequality objectives, and this will eventually allow the completion of the grasping task within adequate safety and operative conditions. By behaving in this way, the system will consequently exhibit the required "agility" in executing its manoeuvres, since they will be faster than in case they were instead executed on a sequential motion basis. The devising of an effective way to incorporate all the inequality and equality objectives within a uniform and computationally efficient task-priority-based algorithmic framework for underwater floating manipulators has been the result of the hereafter outlined research effort.

After presenting the related works in Section 2, the present paper concisely recalls the theory of the proposed task-priority framework in Section 3. The successive Section 4 presents some of the results obtained within the final experiments of the TRIDENT FP7 project. Then a possible extension to the case of dual arm manipulator is given in Section 5. Some final conclusions and perspectives are given in the final Section 6.

2. RELATED WORKS

During early 90s seminal works in control of floating manipulation structures have been carried out at the Woods Hole Oceanographic Institute concerning the design and control compliant underwater manipulators Yoerger et al. (1991) and the coordinated vehicle/arm control for teleoperation Schempf and Yoerger (1992), while the first successful attempts at underwater autonomous intervention were obtained within the ALIVE Evans et al. (2003) (fixed base) and SAUVIM project (free floating) Yuh et al. (1998).

As instead regards the task-priority framework, its first precise formulation appeared in Nakamura (1991) for two equality tasks; which was later generalized to any number of equality tasks within the seminal work Siciliano and Slotine (1991), where each prioritized task was therefore imposed to be satisfied within the null space of all its preceding higher priority ones.

In a very recent paper Kanoun et al. (2011) a framework for handling a hierarchy of both equality and inequality objectives is proposed, where for each of the inequality objectives the cumbersome solution of a set of constrained quadratic problems is required. In their paper Kanoun et al. (2011), the authors also remark again how, within the previous works concerning the task-priority framework, the presence of inequality constraints was never systematically tackled whilst preserving their true meaning, because they were so often replaced by more restrictive equality objectives, arbitrarily chosen inside the validity of the inequality ones, causing an over-constraining problem for the robotic system in hand.

The remark provided in Kanoun et al. (2011) is quite correct whenever the translation into equality objectives is explicitly performed. However, it is the opinion of the authors of this paper that the same remark becomes questionable (at least partially) whenever smooth potential fields, exhibiting a null support over the region where the inequality is satisfied, are instead used for representing inequality objectives; as for example it was just done in the mentioned works Casalino and Turetta (2003); Simetti et al. (2009). The use of finite-support smooth potential fields for representing inequality objectives is what is re-proposed here, now in a systematic way, via the use of the so-called activation functions that will be presented in Section 3.3. And in this way the criticism embedded in the above recalled remark consequently ceases to exist, since the translation of the inequality objectives into restrictive equality ones is not at all performed anymore.

However, as it has been also remarked in Mansard et al. (2009a) and in more details in Mansard et al. (2009b), with the use of the activation functions there might still be problems related to the rapidity of variation (even if with continuity) of the associated solutions, with possible resulting chattering phenomena around the activation thresholds, in case of not sufficiently small sampling times. However such claims cease to be valid whenever the involved pseudo-inversions are performed with suitably chosen smooth regularization factors, as it will be shown in Section 3.3.

The above considerations represent the core ideas supporting the present work, where a framework for task-priority control encompassing both equality and scalar inequality objectives is presented. The proposed approach extends the early work Siciliano and Slotine (1991) by introducing the inequality constraints. Moreover, the proposed framework also results computationally simpler than Kanoun et al. (2011), since it is based on the solution of a sequence of linearly constrained least square problems, rather than on the solution of a sequence of least square problems with linear inequality and equality constraints of increasing dimensions, which is computationally more expensive.

3. TASK-PRIORITY BASED CONTROL OF FLOATING MANIPULATORS

The typical control objectives characterizing the overall grasping task are specified in section 3.1. Then some useful definitions of general use are given, prior to presenting the unifying task-priority based algorithmic framework to be used.

3.1 Control Objectives

The simplest inequality objective that the arm must respect is that all its joints are falling within their physical limits, i.e.

$$q_{i,m} \leq q \leq q_{i,M} \; ; \; i = 1, \ldots, p; \tag{1}$$

with p being the number of arm joints. Furthermore, the arm should avoid its singularity configurations. This can be achieved by maintaining the manipulability measure Yoshikawa (1985) above a minimum value, thus trivially leading to the following inequality type objective

$$\mu \geq \mu_m. \tag{2}$$

For the good operability of the vision algorithms, the vehicle must keep the object grossly centered into its camera field of view. This means that the modulus of the orientation error ξ, formed by the unit vector joining the origin of the object to the camera frame, and the unit vector z axis (the one perpendicular to the image plane) of the camera frame itself, must be below a certain threshold. At the same time, the vehicle must also be closer than a given horizontal distance d_M to the vertical line passing through the object, and between a maximum and minimum height with respect to object located on the sea floor. This consequently translates into the requirement of achieving the following inequalities

$$\|\xi\| < \xi_M \; ; \; \|d\| \leq d_M \; ; \; h_m \leq \|h\| \leq h_M \; ; \qquad (3)$$

where d and h are the horizontal and vertical vectors.

Since the vehicle should avoid configurations with high tilt angle values, this further requires the achievement of the following additional inequality

$$\|\varphi\| \leq \varphi_m, \qquad (4)$$

where φ represents the misalignment vector that the absolute vertical z-axis unit vector forms with respect to the vehicle z-axis one.

Finally, within the fulfillment of the above goals, the end effector must eventually reach the object frame, for then starting the successive grasping phase. Thus the following, now of equality type, objectives also have to be ultimately achieved

$$\|r\| = 0 \;\; ; \;\; \|\vartheta\| = 0, \qquad (5)$$

where r is the position error and ϑ the orientation error.

3.2 Definitions

In this subsection some formal definitions are introduced, which shall be useful for the successive developments. To this aim let us denote a vector associated to a generic control objective defined in the Cartesian space as $s \in \mathbb{R}^M$ and term it as an error-vector. Then its module

$$\sigma \triangleq \|s\|, \qquad (6)$$

will be termed as the error; while its unit vector

$$n \triangleq \frac{s}{\sigma} \; ; \; \sigma \neq 0, \qquad (7)$$

will be termed as the unit error vector. Then, by taking into account that a generic error-vector is subjected to change under the action of the various system velocities, the following Jacobian relationship can be therefore evaluated for each error vector

$$\dot{s} = Hy, \qquad (8)$$

where $y \in \mathbb{R}^N$ is the stacked vector composed of the joint velocity vector $\dot{q}$, plus the stacked vector v of the vehicle velocities, with components on the vehicle frame. Matrix $H \in \mathbb{R}^{M \times N}$ is therefore the Jacobian matrix relating y and $\dot{s}$, with the latter clearly representing the time derivative of vector s performed with respect to the vehicle frame and with components on it. As it instead regards the time derivative $\dot{\sigma}$ of a generic error, the following holds:

$$\dot{\sigma} = n^T Hy. \qquad (9)$$

To each error variable σ, associated to a corresponding objective, let us also associate a so-called error reference rate $\dot{\bar{\sigma}}$ of the form

$$\dot{\bar{\sigma}} \triangleq -\gamma(\sigma - \sigma^o)\beta(\sigma), \qquad (10)$$

where γ is the error gain, and where for an equality objective, σ^o is the target point and $\beta(\sigma) \equiv 1$. Instead, for an inequality objective of the type $\sigma \leq \sigma^o$, σ^o is the threshold value and $\beta(\sigma)$ is a binary function that is zero if $\sigma < \sigma^o$ and one otherwise. $\beta(\sigma)$ is similarly defined for the case of objectives of the type $\sigma \geq \sigma^o$.

In case it could be exactly assigned to its corresponding error rate $\dot{\sigma}$, (10) would guarantee the achievement of the associated objective. However, for inequality objectives, it would consequently impose $\dot{\sigma} = 0$ to whatever point is located inside the interval of validity of the inequality objective itself. In correspondence of such inner points the error rate zeroing condition should instead be relaxed, just for allowing a system mobility increase which might be necessary (or at least helpful) for also achieving other control objectives. Such a relaxation aspect will be dealt with in subsection 3.3.

Finally, directly associated to a reference error rate $\dot{\bar{\sigma}}$, let us also consider the so-called reference error-vector rate, simply defined as

$$\dot{\bar{s}} \triangleq n\dot{\bar{\sigma}}, \qquad (11)$$

that in correspondence of equality control objectives requiring the zeroing of error σ, trivially translates into the following

$$\dot{\bar{s}} = -\gamma s, \qquad (12)$$

whose evaluation can be performed in a direct way (i.e. without the preliminary evaluation of the unit error vector n).

3.3 Managing the Highest Priority Inequality Objective

Let us start by considering the highest priority task. Since, as mentioned before, such a task corresponds to a scalar inequality objective, the control action should drive the error σ_1 towards its validity interval (when σ_1 is outside) and should do nothing when the inequality condition is satisfied (when σ_1 is inside). From now on, to shorten the terminology, let us term such kind of tasks as *inequality tasks*.

The main idea is to use an "activation function" α_1 to activate/deactivate the inequality task as the corresponding condition is satisfied or not. To this aim, let us introduce α_1, which is a suitable smooth activation function of σ_1, that is a left or right window sigmoid function. In particular, $\alpha_1 = 1$ whenever σ_1 is outside of its associated inequality, followed by a suitable transition zone where $0 < \alpha_1 < 1$, and finally $\alpha_1 = 0$ and σ_1 well within its validity interval.

Then, let us consider the linear manifold of solutions of the following linear quadratic optimization problem

$$\mathcal{S}_1 \triangleq \left\{ y = \arg\min_y \left\| \alpha_1 \dot{\bar{\sigma}}_1 - \alpha_1 n_1^T H_1 y \right\|^2 \right\}, \qquad (13)$$

which is

$$y = (\alpha_1 n_1^T H_1)^{\#} \alpha_1 \dot{\bar{\sigma}}_1 + \left[I - (\alpha_1 n_1^T H_1)^{\#} \alpha_1 n_1^T H_1 \right] z_1, \qquad (14)$$

where z_1 is an arbitrary vector which shall be used later to perform the successive tasks. The notation $(\cdot)^{\#}$ refers to the regularized pseudo inverse (see Ben-Israel and Greville (2003) for a complete review on pseudo inverses), which for a row vector (as it is $n_1^T H_1$) can be written as:

$$A^{\#} = \frac{A^T}{A^T A + \bar{p}(\|A\|)}, \qquad (15)$$

where $\bar{p}(\|A\|)$ is a bell-shaped, finite support, positive scalar function of the norm of vector A, which is used to prevent $A^{\#}$ from growing unbounded whenever A is close to zero.

Now the main idea to obtain a smooth activation of the inequality task (when σ_1 is outside its validity interval) and its deactivation (whenever inside) is to use a regularizing function $p(\cdot)$ that, differing from $\bar{p}(\cdot)$ in (15), is now dependent not only on the norm of the product $\alpha_1 n_1^T H_1$, but also explicitly on α_1, in order to obtain the required smoothness for all the values of α_1. Among the possible choices, the one used in TRIDENT is simply

$$p(\alpha_1, \|\alpha_1 n_1^T H_1\|)) \triangleq (1-\alpha_1) + \bar{p}(\|n_1^T H_1\|). \tag{16}$$

With the use of such regularizing function, the expression of the pseudo inverse in (14) becomes

$$(\alpha_1 n_1^T H_1)^{\#} = \frac{\alpha_1 H_1^T n_1}{\alpha_1^2 n_1^T H_1 H_1^T n_1 + (1-\alpha_1) + \bar{p}(\|n_1^T H_1\|)}. \tag{17}$$

Now to show that the above equation exhibits a smooth behavior, let us start by assuming that the vector $n_1^T H_1$ is not singular. This implies that $\bar{p} = 0$. Then let us define $Q_1 \triangleq \left[I - (\alpha_1 n_1^T H_1)^{\#} \alpha_1 n_1^T H_1\right]$ and let us consider the following three possible cases:

(1) if $\alpha_1 = 1$ then $p = 0$ and (17) simply reduces to the standard pseudo inverse of vector $n_1^T H_1$. This implies that Q_1 is an orthogonal projector of rank $N-1$, and $\dot{\sigma}_1 = \dot{\bar{\sigma}}_1$;
(2) if $\alpha_1 = 0$ then $(\alpha_1 n_1^T H_1)^{\#} = 0$. As a consequence, Q_1 is the identity matrix of rank N, and $\dot{\sigma}_1 = n_1^T H_1 z_1$; $\forall z_1$;
(3) if $0 < \alpha_1 < 1$, the regularization makes $(\alpha_1 n_1^T H_1)^{\#}$ smoothly evolve between the previous two cases, and the same holds for matrix Q_1 (which in this case is no more an orthogonal projector). Furthermore note that the corresponding error rate $\dot{\sigma}_1$ varies from $\dot{\bar{\sigma}}_1$ to $n_1^T H_1 z_1$.

As a final remark note that in case the norm of vector $n_1^T H_1$ exhibits a null or quasi-null value (due to a singular posture of the robot), the term $\bar{p}(\cdot)$ in (16) still prevents the pseudo inverse to grow unbounded, as in (15).

Having tackled the problem of smooth activation and deactivation of a single inequality task, let us introduce the following more compact notation:

$$G_1 \triangleq \alpha_1 n_1^T H_1 \; ; \; \rho_1 \triangleq G_1^{\#} \alpha_1 \dot{\bar{\sigma}}_1 \; ; \; Q_1 \triangleq \left[I - G_1^{\#} G_1\right]. \tag{18}$$

The above philosophy can be applied to each of the remaining inequality objectives, using only the mobility space left free by its preceding ones. This can be done as the result of the following sequence of nested minimization problems

$$\mathcal{S}_i \triangleq \left\{ y = \arg \min_{y \in \mathcal{S}_{i-1}} \|\alpha_i \dot{\bar{\sigma}}_i - G_i y\|^2 \right\}, \; i = 2, \ldots, k \tag{19}$$

with k indexing the lowest priority inequality objective.

A simple algebra (see Casalino et al. (2012) for the details) allows translating the above minimization sequence into the following algorithmic structure, after the initialization $\rho_0 = 0$; $Q_0 = I$ then for $i = 1, \ldots, k$:

$$\begin{aligned} \hat{G}_i &\triangleq G_i Q_{i-1} \\ T_i &\triangleq \left(I - Q_{i-1} \hat{G}_i^{\#} G_i\right) \\ \rho_i &= T_i \rho_{i-1} + Q_{i-1} \hat{G}_i^{\#} \alpha_i \dot{\bar{\sigma}}_i \\ Q_i &= Q_{i-1}(I - \hat{G}_i^{\#} \hat{G}_i) \end{aligned} \tag{20}$$

thus ending up with the final control law

$$y = \rho_k + Q_k z_k \;\; ; \;\; \forall z_k, \tag{21}$$

where the residual arbitrariness $Q_k z_k$ has to be used for managing the remaining equality type control objectives, as indicated in the following subsection.

3.4 Managing Lower Priority Equality Objectives

By now restarting at the $k+1$ priority level, where the highest priority equality task is located, we now encounter the following linearly constrained linear quadratic minimization problem

$$\mathcal{S}_{k+1} \triangleq \left\{ y = \arg \min_{y \in \mathcal{S}_k} \|\dot{\bar{s}}_{k+1} - H_{k+1} y\|^2 \right\}, i = k+1, \cdots, L \tag{22}$$

where the use of the error-vector $\dot{\bar{s}}_{k+1}$ has been preferred to avoid ill-definitions of the otherwise needed unit vector n_{k+1} in the proximities of $\sigma_{k+1} = 0$. The cost of this choice is requiring, for each equality objective, three degrees of mobility instead than a sole one, as it is for each inequality objectives.

The resulting global algorithm now extends to the final L-th objective, leading to the final value for the control action

$$y = \rho_L + Q_L z_L, \tag{23}$$

where the residual arbitrariness space $Q_L z_L$ eventually serves for assigning motion priorities between the arm and the vehicle. For instance this can be done via the following least-priority ending task

$$y = \arg \min_{y \in \mathcal{S}_L} \|v\|^2 \tag{24}$$

which would always constrain the vehicle motions to solely be the strictly necessary ones.

3.5 Final Remarks

The presented task-priority-based control structure is invariant with to the addition, deletion, substitution of control objectives, and to changes in their priority ordering, thus constituting an invariant core potentially capable of supporting intervention tasks beyond the object grasping ones. However it solely represents the so-called Kinematic Control Layer (KCL) of the overall control architecture, in charge of real-time generating the system velocity vector reference y. An adequate underlying Dynamic Control Layer (DCL), acting at the level of vehicle thrusters and arm joint torques, must then take care of tracking at best such a velocity reference.

4. EXPERIMENTAL TRIALS

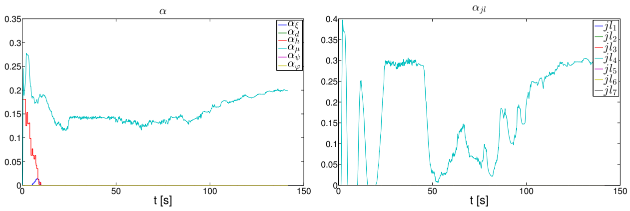
This section will present some of the results of the final experiments of the TRIDENT project in Port Sòller, Majorca. Figure 2 shows some pictures taken from the

(a) (b) (c) (d)

Fig. 2. Experimental trial in Majorca harbour: snapshots taken from the on-board camera

on-board camera and depicts the phases of the floating manipulation until the successful grasp.

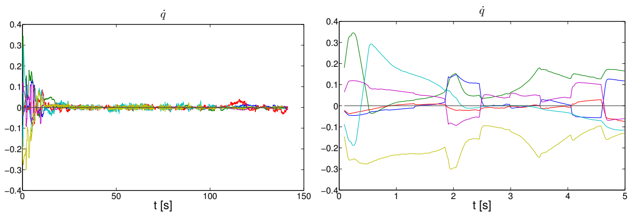
Figure 3 reports the time history of the activation functions, showing how the camera centering and camera height tasks were briefly active at the start of the trial, while the manipulability task was basically always active, preventing the arm from stretching too much and losing dexterity. The figure also shows how one joint was near the end of race, but the system prevented it to violate such a bound.



(a) (b)

Fig. 3. Majorca harbour trials: time history of the α functions of the set rate tasks

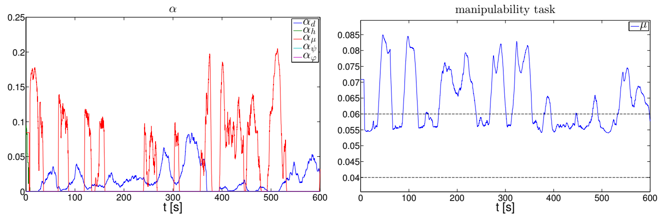
The successive Fig. 4(a) shows the commanded $\dot{q}$ for the whole period of the test. Figure 4(b) represents a zoom of the first five seconds, highlighting the fact that the $\dot{q}$ is continuous. The "step" changes are due to the relatively slow updates (2Hz) coming from the vision system.



(a) (b)

Fig. 4. Majorca harbour trials: time history of the arm velocity reference $\dot{q}$: (a) complete graph (b) zoom to show the continuity

The successive figures are instead related to a second trial, where the end-effector was commanded to stay on top of the blackbox as much as possible, to see how the control was able to compensate for the disturbances acting on the vehicle. The trial lasted about 10 minutes, where the hand was successfully kept into a commanded grasp position. Figure 5(a) shows the time history of the activation functions α, while Fig. 5(b) shows how the control successfully maintained a good manipulability measure over the whole trial.



(a) (b)

Fig. 5. Majorca harbour trials: (a) time history of the α functions (b) manipulability measure kept inside its bounds

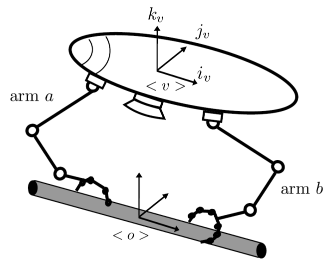


Fig. 6. Dual arm configuration with the relevant frames

5. EXTENSION TO DUAL ARM FLOATING MANIPULATION

Let us now refer to the system of Fig. 6, where the vehicle is now endowed with two separate arms. Let us assume that the two arms have separately grasped a common object. In order to transport it to a goal location, the whole system must be suitable coordinated to also comply with the kinematic constraint that the object itself imposes, i.e.

$$J^a \dot{q}^a + Sv = J^b \dot{q}^b + Sv, \tag{25}$$

where J^a is the Jacobian of the arm a transferred to an object frame $< o >$, and where J^b is similarly defined for 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. Since the vehicle only adds rigid body movements to the grasped object, it does not create problems from the point of view of the kinematic constraints. Then, as it already appears in (25), the constraint can be simplified to

$$J^a \dot{q}^a = J^b \dot{q}^b. \tag{26}$$

A simple strategy to deal with this situation is to consider the following equality constraint

$$\begin{bmatrix} J^a & -J^b \end{bmatrix} \begin{bmatrix} \dot{q}^a \\ \dot{q}^b \end{bmatrix} \triangleq \hat{J}\dot{q} = 0 \tag{27}$$

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

$$\mathcal{S}_1 \triangleq \left\{ \dot{q} = \arg\min_{\dot{q}} \left\| \hat{J}\dot{q} \right\|^2 \right\}, \tag{28}$$

whose solution is very simple and results to be

$$\dot{q} = \rho_1 + Q_1 z_1 = 0 + (I - \hat{J}^{\#}\hat{J}) z_1 \;\; ; \;\; \forall z_1. \tag{29}$$

As seen in the previous sections, all the subsequent tasks will have to be performed exploiting the residual arbitrariness represented by z_1, which is the sole one that respects the kinematic constraint.

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

$$\mathcal{S}_2 \triangleq \left\{ \dot{q} = Q_1 z_1 : z_1 = \arg\min_{z_1} \left\| A_2 \Sigma_2 - \hat{G}_2 z_1 \right\|^2 \right\}, \quad (30)$$

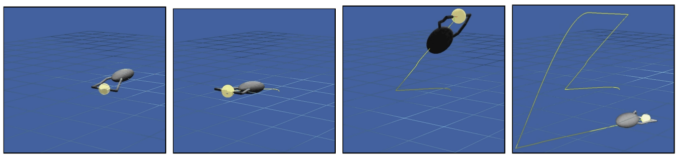
where we have preliminarily let

$$A_2 \triangleq \begin{bmatrix} \alpha_2^a & 0 \\ 0 & \alpha_2^b \end{bmatrix} ; \hat{G}_2 \triangleq A_2 \begin{bmatrix} {n_2^a}^T H_2^a & 0 \\ 0 & {n_2^b}^T H_2^b \end{bmatrix} Q_1, \quad (31)$$

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 same procedure can be repeated as in the single arm case for all the subsequent tasks, by considering the stacked vector $\dot{q}$ of all joint variables and a diagonal matrix of the relevant Jacobians of the two arms for each specific task.

As it can be seen, in the dual arm case multidimensional inequality tasks are naturally appearing. Thus, current works are focused on the extension of the proposed technique to also encompass such kind of tasks. This would allow to seamlessly integrate previous results of the authors on dual arm manipulation Casalino and Turetta (2003); Casalino et al. (2005), as reported in Fig. 7.



(a) (b) (c) (d)

Fig. 7. Snapshots of a I-AUV performing dual arm manipulation

6. CONCLUSIONS AND FUTURE WORK

The paper has presented a unifying framework for task-priority based control of floating manipulators, developed and then used within the EU FP7 TRIDENT project Sanz et al. (2012), which is actually the first one where agile manipulation could be effectively achieved by part of an underwater floating manipulator.

The current research is focused on extending the core framework to more complex systems and operational cases, such as for instance multi-arm systems (as shown in the previous section) and/or even cooperating ones. Indeed, the authors are now working on an Italian funded project called MARIS whose aim is to extend the presented framework to the case of cooperative I-AUVs.

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