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Full Length Article

Whole body control of a dual arm underwater vehicle manipulator system☆,☆☆

E. Simetti*, G. Casalino

Interuniversity Research Center on Integrated Systems for the Marine Environment (ISME), Department of Computer Science, Bioengineering, Robotics, and System Engineering (DIBRIS), University of Genova, Via Opera Pia 13, 16145 Genova, Italy

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ABSTRACT

This paper presents a whole body control framework for the control of a dual arm underwater vehicle manipulator system developed in the context of the MARIS Italian research project, which deals with the control and coordination of underwater vehicles for manipulation and transportation problems. The proposed framework is the extension of the one used in the successful TRIDENT FP7 project that has been improved to be able to deal with multidimensional inequality control objectives. After the presentation of the mathematical background, the paper presents some simulation results showing the good performances of the proposed algorithm.

1. Introduction

Underwater vehicle manipulator systems (UVMS), also called Intervention Underwater Autonomous Vehicles (I-AUV), have been increasingly studied and exploited in the last few years. Their goal is to automatize actions currently performed by Remotely Operated Vehicles (ROVs), which have the fundamental drawback of requiring expensive support vessels equipped with dynamic positioning systems and capable of handling the tether cable, and manned submersibles, which instead require a human operator and thus can only be used for a few hours with the additional problem of placing a human being in a dangerous environment.

For these reasons, the research in this field has seen a steady increase in the past two decades. During early 90s, seminal works have been carried out at the Woods Hole Oceanographic Institute concerning the design and control compliant of underwater manipulators (Yoerger, Schempf, & DiPietro, 1991) and the coordinated vehicle/arm control for tele-operation (Schempf & Yoerger, 1992). At the end of that decade, major breakthroughs were achieved in the pioneering AMADEUS project (Lane et al., 1997), which covered dual-arm underwater manipulation control aspects, in the UNION project Rigaud et al. (1998) where the mechatronic assembly of an autonomous UVMS has taken place for the first time, and in the SAUVIM project (Marani, Choi, & Yuh, 2008; Yuh et al., 1998) where the first successful attempts at underwater autonomous intervention were accomplished. A nice survey on the developed control architectures for underwater robots until late 90s can be found in Yuh (2000).

Another important milestone has been achieved with the TRIDENT project (Sanz et al., 2012) that has demonstrated the autonomous recovery of a black-box from the sea floor (Simetti, Casalino, Torelli, Sperindé, & Turetta, 2013; 2014), where for the first time a vehicle and an arm of comparable masses were controlled in a coordinated manner.

Recently, the TRITON Spanish research project (Sales, Santos, Sanz, & Dias, 2014) is instead focusing on underwater intervention on a permanent observatory's panel, and has achieved some *practical* results on floating valve-turning operations (Cieslak, Ridao, & Giergiel, 2015), although the proposed approach does not deal with the discontinuity problems that might arise with the use of the task priority framework near singularities. Furthermore, it uses the notion of "concurrent" tasks whose solution is summed to the solution of those following the task priority framework, thus violating their priorities. The panel valve-turning scenario is also the subject of the PANDORA project (Lane, Maurelli, Kormushev, Carreras, Fox, & Kyriakopoulos, 2012), which focuses on the problem of persistent autonomy. Another on-going EU project is DexROV (Gancet et al., 2015), which is dealing with the inspection and maintenance in presence of communication latencies.

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* Corresponding author.
E-mail address: enrico.simetti@unige.it (E. Simetti).

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The ARROWS project (Allotta et al., 2015b) proposes to adapt and develop low cost autonomous underwater vehicle technologies to significantly reduce the cost of archaeological operations, covering the full extent of archaeological campaign. Within such a context, Allotta, Conti, Costanzi, Fanelli, Meli, and Ridolfi (2015a) have proposed a modeling of the UVMS and a suitable grasp planning strategy and a decentralized cooperative control strategy (Conti, Meli, & Ridolfi, 2015), which focuses on the control of a team of UVMSs performing a transportation task, but does not take into account all the inequality control objectives that each UVMS needs to satisfy.

Finally, the Italian funded MARIS project (Casalino et al., 2014), which is the context where the present work has been developed, focuses on the development of a unifying control framework capable of managing single, dual arm and cooperative UVMSs, tackling the problems of manipulation and transportation in underwater scenarios (Manerikar, Casalino, Simetti, Torelli, & Sperindé, 2015a, 2015b; Simetti, Casalino, Manerikar, Torelli, Sperindé, & Wanderlingh, 2015).

One of the important aspects in the control of UVMS is how to effectively exploit all their degrees of freedom (DOF) for accomplishing the required tasks. This problem is further increased by analysing the actual tasks that an UVMS has to tackle. Indeed, aside from positioning the end-effector over the blackbox or the pipe to be grasped, most if not all the other tasks are dedicated to maintaining the safety of the system (avoiding the arm's joint limits, avoiding self collisions and collision with other vehicles) or certain operative configurations (i.e. keeping the object grossly centerd, avoiding camera occlusions) and thus are a prerequisite for the final end-effector positioning task. These safety/operational tasks are usually accomplished whenever they are under, above or between some given thresholds, because they are inequality control objectives.

The seminal results on task/operational-based control (Khatib, 1987; Nakamura & Hanafusa, 1986), and their successive extension with the introduction of priorities between tasks (Nakamura, 1991; Siciliano & Slotine, 1991) did not integrate inequality control objectives efficiently. Indeed, they were converted to equality ones, overconstraining the system. This is due to the fact that, in the original formulation, activating (inserting) or deactivating (deleting) a task implies a discontinuity in the null space projector, which leads to a discontinuity in the control law (Lee, Mansard, & Park, 2012).

In the last decade, major research efforts have been spent in order to incorporate inequality control objectives in the task-based control paradigm. In Mansard, Remazeilles, and Chaumette (2009b) a new inversion operator is introduced for the computation of a smooth inverse with the ability of enabling and disabling tasks, and has been extended to the case of a hierarchy of tasks in Mansard, Khatib, and Kheddar (2009a). However, the major problem within that work is that it requires the computation of all the combinations of possible active and inactive tasks, which grows exponentially.

Another interesting approach is given in Lee et al. (2012). The idea is to modify the reference of each task that is inserted or being removed, in order to comply with the already present ones, in such a way to smooth out any discontinuity. However, the algorithm requires $m!$ pseudo inverses with m number of tasks. The authors provide also approximate solutions, which are suboptimal whenever more than one task is being activated/deactivated (in *transition*).

Previous works of the authors dealt with the control of underwater free floating manipulators (Casalino, Zereik, Simetti, Torelli, Sperindé, & Turetta, 2012a, 2012b; Simetti, Casalino, Torelli, Sperindé, & Turetta, 2014) in the context of the TRIDENT project. In such works, all the tasks except the end-effector position control were represented by scalar inequality tasks. The activation and deactivation of scalar tasks was tackled in the prioritized control.

This work generalizes the framework presented in Simetti et al. (2014) and allows its use to the dual arm scenario of the MARIS project, where multidimensional inequality tasks naturally arise. It retains the simplicity of the original task-priority framework (Siciliano & Slotine, 1991) since it only uses pseudo-inverses. Tasks are activated and deactivated via the use of an activation matrix. The possible discontinuities that can arise with the use of an activation matrix (Mansard et al., 2009a, 2009b) are eliminated with the use of a novel task-oriented regularization and the singular value oriented one. This allows to treat inequality control objectives efficiently, as their corresponding tasks are deactivated whenever the system is inside the validity region of the inequality objective, avoiding any overconstraining of the system.

The work is structured as follows. Section 2 introduces some definitions and the main control objectives of the dual arm UVMS. Section 3 presents the underlying task priority framework that allows the UVMS to concurrently carry out its different tasks. Simulation results are presented in Section 4, and some final conclusions are given in Section 5.

2. Definitions and preliminaries

Before starting the discussion we first introduce some notation and definitions. Then, the control objectives of the UVMS are presented and finally the basics of pseudo inverse problems are recalled.

2.1. Notation

Vectors and matrices are expressed with a bold face character, such as $\boldsymbol{M}$, whereas scalar values are represented with a normal font such as γ. Given a matrix $\boldsymbol{M}$:

- $M_{(i,j)}$ indicates the element of $\boldsymbol{M}$ at the ith row and jth column;
- $\boldsymbol{M}_{\{k\}}$ refers to the kth row of $\boldsymbol{M}$;
- $\boldsymbol{M}^{\#}$ is the exact generalized pseudo-inverse (see Ben-Israel and Greville, 2003 for a review on pseudo-inverses and their properties), i.e. the pseudo inverse of $\boldsymbol{M}$ performed without any regularizations.

Further, less used, notation is introduced as needed.

2.2. Definitions

Let us consider a free floating dual arm UVMS such as the one depicted in Fig. 1, and in order to avoid any confusion, let us report hereafter some definitions often used in this paper:

- the system configuration vector $\boldsymbol{c} \in \mathbb{R}^n$, which for a dual arm UVMS is

$$\boldsymbol{c} \triangleq \begin{bmatrix} \boldsymbol{q}_a \\ \boldsymbol{q}_b \\ \boldsymbol{\eta} \end{bmatrix}, \tag{1}$$

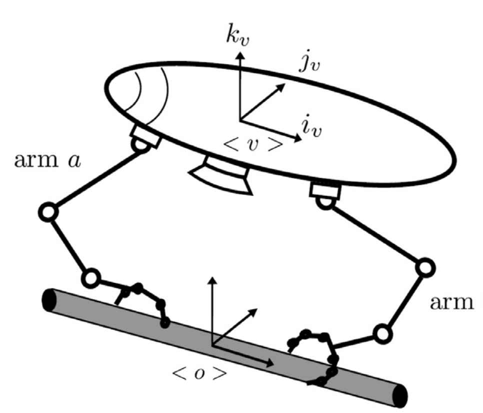

Fig. 1. Dual arm configuration with the relevant frames.