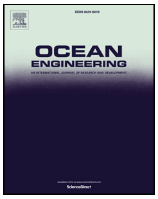
Ocean Engineering 164 (2018) 40–54

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Task priority control of underwater intervention systems: Theory and applications

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ARTICLE INFO

Keywords:
Task priority control
Intervention autonomous underwater vehicles
Remotely Operated Vehicles
Kinematic control
Underwater Vehicle Manipulator Systems

ABSTRACT

This paper presents a unifying task priority control architecture for underwater vehicle manipulator systems. The proposed control framework can be applied to different operative scenarios such as waypoint navigation, assisted teleoperation, interaction, landing and grasping. This work extends the results of the TRIDENT and MARIS projects, which were limited to the execution of grasping actions, to other applications taken from the DexROV and ROBUST projects. In particular, simulation results show how the control framework can be used, for example, for pipeline inspection scenarios and deep sea mining exploration.

1. Introduction

During the last 20 years, Autonomous Underwater Vehicles (AUVs) have been widely used as a tool for mapping the seafloor using optical and acoustic sensors, with applications to dam inspection (Ridao et al., 2010), marine geology (Wynn et al., 2014; Urabe et al., 2015) and underwater archaeology (Drap et al., 2008; Bingham et al., 2010) to mention but a few. After years of research, few autonomous platforms are already available in the market (Alvarez et al., 2009; Ribas et al., 2012), most of them able to perform side scan sonar and bathymetric multi-beam surveys. A recent survey (Yuh et al., 2011) reports a list of commercial platforms and applications of AUVs.

However, a large number of applications exist that go beyond the survey capabilities. A number of them stem from the oil and gas industry, such as the maintenance of submerged oil wells, cabled sensor networks and pipelines. In fact, Chevron has, since 2007, an on-going program for the employment of resident Intervention AUVs (I-AUVs) to provide better and more frequent inspections, earlier monitoring, and reduced field maintenance and development costs (Gilmour et al., 2012). Nowadays, these tasks require the use of work-class Remotely Operated Vehicles (ROVs) deployed from dynamic positioning vessels making them very expensive.

To respond to this increasing demand, research in marine robotics has started focusing on the development of Underwater Vehicle Manipulator Systems (UVMS). Since early 90s, different pioneering works were carried out on the control of compliant underwater manipulators (Yoerger et al., 1991), coordinated vehicle/arm control for teleoperation (Schempf and Yoerger, 1992), and during the ODIN (Choi et al., 1994) and OTTER (Wang et al., 1995) projects. Successively, within the UNION project (Rigaud et al., 1998) the first mechatronic assembly of an autonomous UVMS was achieved. Between 1993 and 2000, the AMADEUS project (Lane et al., 1997) developed grippers for underwater manipulation (Angeletti et al., 1998) and studied the problem of dual arm autonomous manipulation (Casalino et al., 2001), demonstrating these features in water tank experiments. The successive decade was characterized by different field demonstrations, among which we can cite the SWIMMER project (Evans et al., 2001) and the ALIVE project (Evans et al., 2003; Martyet al, 2004) that achieved autonomous docking into a seabed docking station or ROV-friendly panels, and the SAUVIM project (Yuh et al., 1998; Marani et al., 2008), which demonstrated the capability of searching and recovering an object whose position was roughly known a priori.

Concurrently, research in industrial robotics focused on how to effectively specify the control objectives of a robotic system, especially for redundant systems. The task-based control (Nakamura and Hanafusa, 1986), also known as operational space control (Khatib, 1987), defines control objectives in a coordinate system that is directly relevant to the task that needs to be performed, rather than in the generalized coordinates of the robotic system. Such an idea was immediately enhanced by the introduction of the concept of task priority (Nakamura, 1991). In that work, a primary task was executed, and a secondary task was accomplished (or attempted) only in the null space of the primary one, in order to guarantee the invariance of the main task w.r.t. (with respect to) the secondary one. This concept was later generalized to any number of task-priority levels in the seminal work (Siciliano and Slotine, 1991). However, it must be noted how the

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https://doi.org/10.1016/j.oceaneng.2018.06.026
Received 7 December 2017; Received in revised form 24 April 2018; Accepted 9 June 2018

position control of the end-effector was always the highest priority task, and safety tasks such as joint limits were only *attempted* at lower priority.

Given that an UVMS is a robotic system characterized by a high number of degrees of freedom, within the TRIDENT project (Sanz et al., 2013) these two research trends were merged. A novel task priority resolution mechanism, which managed equality and scalar-only inequality control objectives, was developed and exploited for the first time for the coordinated control of a floating base and a manipulator for performing autonomous floating intervention (Simetti et al., 2014). A blackbox recovery intervention was experimentally proved in a harbour environment. Shortly after TRIDENT, the PANDORA project has demonstrated autonomous free-floating valve-turning operation on a subsea panel using a learning by demonstration paradigm (Carrera et al., 2014) and a task-priority kinematic control approach (Cieslak et al., 2015). However the adopted task priority framework only dealt with equality control objectives and an ad-hoc solution was devised to manage the joint limit safety task, therefore it does not represent a general solution.

Successively, the concepts developed in the TRIDENT project were further enhanced within the MARIS project, with the definition of a task priority framework able to activate and deactivate equality/inequality control objectives of any dimension (i.e. not limited to scalar ones) depending on the system current needs (Simetti and Casalino, 2016). This feature allows the user to put safety and operational-enabling objectives at the highest priority, as they should be. Experiments in free floating grasping have been conducted, with multiple attempts to test the repeatability and robustness of the control (Simetti et al., 2017). The MARIS project also studied the extension of the control architecture to cooperative agents (Simetti and Casalino, 2017). Finally, recent studies on I-AUVs can be found in (Farivarnejad and Moosavian, 2014; Allotta et al., 2015; Conti et al., 2015).

Nowadays, the authors are involved in two other projects where UVMSs are employed, namely the EU H2020 DexROV and ROBUST projects. The DexROV project (Di Lillo et al., 2016) main goal is to delocalize on shore the manned support to ROV operations as much as possible, reducing the crew on board the support vessel and consequently the costs and risks of the whole operation. The delocalization is performed using satellite communications between the support ship and the remote control center. Therefore, only high level commands are sent through the satellite channels and forwarded to the ROV, which must execute them in a semi-autonomous manner. The ROBUST project (ROBUST website, 2016) aims to use robotic technologies for the exploration of deep-water mining sites, especially manganese nodule fields. The main idea is to perform in-situ measurements of the nodules, to identify if they contain Rare Earth Elements, which are particularly sought after in the market.

This paper presents a unifying control architecture for the control of UVMSs, both in the case of partial (assisted) teleoperation and fully autonomous operation. The architecture handles inequality control objectives without overconstraining the system, it coordinates the arm and vehicle movements thanks to a parallel task-priority inversion scheme (section 2.10), which is also suitable for multi-rate control, and it also manages the presence of vehicle underactuations to the best extent possible with the simple addition of a control task (section 2.9).

With respect to previous publications, this work does not consider only a grasping scenario, as it was the case of the TRIDENT and MARIS projects, but it extends the framework and shows its flexibility in tackling different operative scenarios, presenting the most recent results of the DexROV and ROBUST projects. In fact, the same architecture can execute the required operations as long as the corresponding *actions* are defined, with the advantage of having a unique controller at the kinematic level, simplifying the overall implementation and allowing greater modularity, as many control *tasks* are common to more than one *action*. The present work's contributions are listed as follows:

C_1 It presents, in a self contained way, all the properties of the proposed task priority framework, omitting only the mathematical details presented in (Simetti and Casalino, 2016).

C_2 It shows how the proposed approach can be used for both autonomous operation and assisted teleoperation, either if the user wants to control some of the degrees of freedom, or even if he/she desires to control only the end-effector. This is a requirement coming from the DexROV project;

C_3 It presents the integration of force regulation at the kinematic level, for example to carry out the inspection of a pipeline as needed in the DexROV project, validated through dynamic simulations, including different rates for the kinematic and dynamic control layers, vehicle added masses and Coriolis effects, thruster dynamics and actuator saturations;

C_4 It discusses how a safe navigation action and how landing in front of a specific target can be implemented, again validated through dynamic simulations, as they are two of the operations needed in the ROBUST project for deep-mining exploration.

The paper is organized as follows. Section 2 recaps the theory behind the developed task priority control framework. Then, the flexibility of the proposed architecture in tackling many different kind of applications, spanning all the aforementioned projects, is highlighted in section 3. In section 4, the most recent simulation results of the DexROV and ROBUST projects are shown. Section 5 presents the current open problems and research trends. Finally, some conclusions are given in section 6.

2. The control framework: theory

The control framework presented in this paper is based on the cascade of blocks shown in Fig. 1. In particular, the architecture is constituted by three main blocks:

1. The Mission Manager is in charge of supervising the execution of the current *mission*, and generates the corresponding *actions* to be executed by the Kinematic Control Layer. As it will be explained later in section 2.4, an action is any prioritized list of control objectives to be concurrently achieved, and a mission is a sequence (or graph) of actions.
2. The Kinematic Control Layer (KCL) implements the proposed task priority control framework, and is in charge of reactively accomplishing the *control objectives* that make up the current action to be executed, generating the desired system velocity vector.
3. The Dynamic Control Layer (DCL) tracks the desired system velocity vector by generating appropriate force/torques commands for the vehicle and the manipulator.

The paper focuses on the Kinematic Control Layer, since it is the one implementing the proposed task priority approach. The interfaces with the higher level (Mission Manager) and the lower one (DCL) are highlighted whenever relevant.

2.1. General definitions

Let us introduce two definitions that will be used thoroughly in this paper:

- The system configuration vector $\boldsymbol{c} \in \mathbb{R}^n$ of the UVMS as $\boldsymbol{c} \triangleq [\boldsymbol{q} \quad \boldsymbol{\eta}]^T$, where $\boldsymbol{q} \in \mathbb{R}^l$ is the arm configuration vector and $\boldsymbol{\eta} \in \mathbb{R}^6$ is the vehicle *generalized coordinate position* vector, which is the stacked vector of the position vector $\boldsymbol{\eta}_1 \triangleq [x \quad y \quad z]^T$, with components in the inertial frame $\langle w \rangle$, and the orientation vector $\boldsymbol{\eta}_2 \triangleq [\phi \quad \theta \quad \psi]^T$, the latter expressed in terms of the three angles roll, pitch, yaw (applied in the yaw-pitch-roll sequence (Perez and Fossen, 2007)). The possible singularity arising when the pitch angle is near $\pi/2$ is