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Position/force operational space control for underwater manipulation

Corina Barbalata [a,*,1], Matthew W. Dunnigan [b], Yvan Petillot [b]

[a] *Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, USA*
[b] *School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK*

HIGHLIGHTS

- A position/force control architecture is designed for an underwater manipulator.
- The control law handles approximated contact forces with the environment in the case when a force sensor is not available.
- Incorporating an estimate of the dynamic model and the theory of sliding mode theory leads to a robust and stable behaviour.
- A valid alternative to the Impedance Control, handling some of the challenges present in the Impedance control.
- Experimental results prove the validity of the system.

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ABSTRACT

An underwater manipulator is a complex system, highly non-linear and subject to disturbances caused by underwater effects. To obtain a reliable system, robust control strategies have to be designed for the manipulator. The main contribution of this paper is the development of the low-level position/force control structure for an underwater manipulator. The proposed control strategy is planned in the operational space and combines together the parallel control structure for position/force applications with the sliding mode theory and the manipulator model information. The dynamic model of the system incorporates the hydrodynamic effects and an approximation of the end-effector force contact with the environment. This paper presents a method for computing the interaction force at the end-effector in the absence of a force–torque sensor. The control structure is validated through a Lyapunov-stability approach and experimental results. The control structure is tested on a 6 degrees-of-freedom underwater manipulator interacting with the underwater environment.

1. Introduction

The inspection and surveillance of the oceans is increasingly performed with autonomous vehicles for the oil and gas industry, military applications and various research applications. These systems are commercially available and there is a constant desire to improve them. Therefore, scientists are interested in extending the autonomy of the robots to interact with the underwater environment. An underwater manipulator placed on a mobile platform is subject to a large number of disturbances such as hydrodynamic effects, sea currents, disturbances caused by the movement of the mobile base and/or large contact forces caused by interaction with the environment.

The underwater manipulation tasks are naturally defined in the operational space while the control actions have to be represented at joint level. Nevertheless, the control structure for underwater manipulators can be designed either in the joint space or in the operational space and further projected to joint space. The advantage of the operational space controllers rests in the fact that the task error is directly minimised by the feedback loop [1].

The operational space control structure is presented in [2] for vehicle and arm coordination as well as for multiple manipulators working together. The experimental results shows the validity of designing the control law in the operational space for the case when multibody systems have to be used to perform the specified tasks. Other control schemes developed in end-effector coordinates for underwater manipulators have been proposed recently in [3,4]. The manipulators are part of vehicle-manipulator systems where the control schemes are designed to handle environmental disturbances and perform accurate end-effector trajectory tracking. The redundancy exploitation of the UVMS is a key factor in solving the task control problem in [5] and [6]. Underwater

* Corresponding author.
E-mail addresses: corinaba@umich.edu (C. Barbalata), m.w.dunnigan@hw.ac.uk (M.W. Dunnigan), y.r.petillot@hw.ac.uk (Y. Petillot).
[1] During this work the author was with the School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK.

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manipulation tasks are controlled through an operational space fuzzy controller in [7]. The authors demonstrate through the simulation results that the proposed strategy can track the desired end-effector position and provides robust performance. The design of the control structure in the workspace is realised in [8] where a complete low-level/high-level control structure is presented for a free-floating manipulator.

A compliant control structure for underwater manipulation is proposed in [9] for applications where the system has to interact with the environment. The paper is focused on the design of the manipulator and the authors state that impedance controllers can be used for force control applications with this manipulator. The control structure for a hydraulic underwater manipulator is presented in [10]. The authors demonstrate the validity of the hybrid position/force control structure for a manipulator with a force sensor through experimental results. The force at the end-effector is directly controlled for underwater manipulation in [11]. The author proposes two direct control schemes for interaction with the environment. In the first control strategy the force error is directly incorporated in the control command from the motion controller. In this case the motion controller is represented through a PID law. In the second control strategy the force error is incorporated in the velocity control law of the system. The output of this control law is further incorporated into the motion controller represented through a sliding mode regulator. The simulation results show that both controllers are robust to uncertainties in the system, hydrodynamic effects and poor performance of the vehicle controller. The control of both position and force for underwater manipulation is presented in [12]. The control system combines the hybrid structure with an impedance controller. The impedance controller is used up to the point where interaction with the environment takes place to ensure a soft contact with the environment. From this point onwards, this control structure is replaced by the hybrid control to ensure the desired interaction force is maintained. A parallel force/position controller is used in [13] for the control of an underwater manipulator placed on an autonomous vehicle. A model free control law is used as the position control structure and through simulation results it is shown that the controller is robust to external disturbances and fulfils the system requirements.

For underwater environments the model based control structures represent one of the main approaches used in the literature for handling the environmental disturbances. These types of controllers can be used to linearise the system and to describe a coupled control architecture for a floating base and manipulator as presented in [14]. In [15] a model based controller is proposed for a 3 degrees-of-freedom (DOF) underwater manipulator. A sliding mode controller is developed for a trajectory tracking application. The sliding mode controller (SMC) represents a robust approach that is able to handle the uncertainties and disturbances from the underwater effects. It has been used for motion tracking control in underwater environments in [16], together with a fuzzy-component for the gain tuning. Based on simulation results the authors conclude that the proposed tuning improves the performances of the SMC controller. A similar approach is presented in [17] where a SMC with fuzzy tuning is implemented for an underwater-vehicle manipulator system. The performance of the system is validated through simulation results with a 5-DOF UVMS for trajectory tracking applications. Through experimental results a SMC controller is evaluated in [18]. The controller is implemented on an underwater three fingered gripper.

The main goal of this paper is to present a novel low-level control structure for an underwater manipulator for applications including trajectory tracking and interaction with the surrounding environment. The novelty of the paper rests in the structure of the controller. Although the sliding mode control law is a well studied approach, it is incorporated into a parallel position/force control strategy for the first time. Previous work in the field either incorporated the control law in a hybrid position/force control law [19,20] or in an impedance approach [21,22]. The main strength of the proposed law is shown through experimental results and consists in the fact that the method handles approximated contact forces with the environment, when a force sensor is not available. Furthermore uncertainties in the system and disturbances created by the contact with the environment are handled by a novel way of incorporating an estimate of the dynamic model with the sliding mode theory.

A model based structure is used in the control law based on the mathematical representation of the system presented in Section 2. The overall control structure using the parallel position/force strategy and a variable structure law is described in Section 3. The experimental set-up used to evaluate the control law is described in Section 4 and the results are presented in Section 5. A few comments on the experimental results are presented in Section 6 followed by the conclusions of the paper in Section 7.

2. Mathematical model

The closed form mathematical model of an underwater manipulator interacting with the environment is represented through Eq. (1).

$$M(\rho)\ddot{\rho} + C(\rho,\dot{\rho})\dot{\rho} + D(\rho,\dot{\rho})\dot{\rho} + g(\rho) + f_f(\rho) = \tau - J^{-1}F \tag{1}$$

where $\rho \in \mathbb{R}^n$ are the joint positions, $\dot{\rho} \in \mathbb{R}^n$ are the joint velocities and $\ddot{\rho} \in \mathbb{R}^n$ are the joint accelerations. $M(\rho) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $C(\rho,\dot{\rho})\dot{\rho} \in \mathbb{R}^n$ is the Coriolis and Centripetal matrix, $D(\rho,\dot{\rho})\dot{\rho} \in \mathbb{R}^n$ is the hydrodynamic drag, $g(\rho) \in \mathbb{R}^n$ is the restoring forces vector, $f_f \in \mathbb{R}^n$ is the friction of the system, $F \in \mathbb{R}^6$ is the vector of interaction forces with the environment and $\tau \in \mathbb{R}^n$ is the vector of generalised forces applied to the manipulator, $J \in \mathbb{R}^{6\times n}$ is the manipulator Jacobian and n is the number of degrees-of-freedom of the manipulator.

The mathematical model is obtained by approximating each link as a cylinder and applying the laws of physics. A recursive implementation is used to compute the overall model, based on the Composite Rigid Body Algorithm [23], the Newton–Euler Algorithm and incorporating the hydrodynamic effects.

$M(\rho)$ is interpreted as the matrix of forces that distributes an acceleration on a stationary system. Each column of the $M(\rho)$ matrix is interpreted as the vector of forces to produce a unit acceleration onto the corresponding link. To compute the values of the column i, it is considered that the links from i to the last link are moving, while the previous links are static. Based on this assumption every joint transmits a force, defined based on the inertial components, onto the subsequent link. The matrix $M(\rho)$ is computed according to:

$$M(\rho) = \begin{bmatrix} M_{11} & \cdots & M_{1n} \\ & \ddots & \\ M_{n1} & \cdots & M_{nn} \end{bmatrix} \tag{2}$$

where

$$M_{ij} = \begin{cases} s_i^T I_i^c s_j & \text{if } i \in \lambda(j) \\ s_i^T I_j^c s_j & \text{if } j \in \lambda(i) \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where $\lambda(j)$ represents the set of parents for joint j and I_i^c is the inertia of the subtree that starts at the rigid body i. The inertia is computed based on the sum of inertias of all links that are part of the subtree:

$$I_i^c = I_i + \sum_{j\in\mu(i)} I_j^c \tag{4}$$

where $\mu(i)$ is the set of the children of joint i.