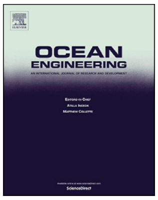
Ocean Engineering 151 (2018) 276–289

Contents lists available at ScienceDirect

Ocean Engineering

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



Redundant actuation system of an underwater vehicle

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ARTICLE INFO

Keywords:
Robotics
Underwater
Redundancy

ABSTRACT

This paper addresses the question of redundancy management of a vectorial actuation system of an underwater robot. The approach focuses on the compensation of the actuators structural imperfections: dead-zone and motor's response disparity. The solution is based on the identification of a correction matrix which highly improves the open-loop response of the actuation system. The effect is formally shown in the linear case approximation. Experimental validation shows the performance of the solution.

1. Introduction

The harsh condition of the underwater environment imposes difficult constraints to be handled by the robotic system. Moreover, recent applications require reactivity, robustness and dependability of the actuation system, as the survey paper (Johansen and Fossen, 2013) clearly underlines.

Major issues refer to the design and management of the system's actuators. Indeed, actuation redundancy plays an instrumental role on these questions. A large number of underwater vehicles use redundant actuation configuration, as, for example, "KAIKO 7000" (Nakajoh et al., 2012) of JAMSTEC or the "ODIN" (Choi et al., 1994) of the University of Hawaii without being exhaustive. Generally speaking, if the underwater vehicle holds more actuators than the 6 Degrees Of Freedom (DOF), the system is considered as over-actuated. Nevertheless, from the geometrical configuration of the thrusters depends the manageability of this redundancy (Fossen, 1994; Garus, 2004). Omerdic and Roberts (2004) addresses the structural redundancy to afford the system with fault tolerance in order to cope with the loss of a thruster. Fuqiang et al. (2013) focuses on the question of homing problem, in the case where the system has lost some of its actuation capability.

The structural redundancy of the system provides the ability to control several tasks, as the task function approach (Mansard, 2006) proposes. For example in Garus (2004), the authors use a configuration matrix of the actuation, allowing for actuators selection according to a secondary function related to dependability ability.

In Hanai et al. (2004) and Hanai et al. (2003) the authors propose to exploit redundancy following a heuristic that minimizes energy, despite a lack of compensation for motor nonlinearities. Chyba et al. (2008) uses an heuristic approach to optimize thrust efficiency.

A good characterization of thruster is needed to design realistic model of the thruster (Pivano, 2008), deals with the identification and design of underwater thruster. Kim et al. (2006) illustrates the difference between a closed loop control and open loop control, and shows that a good thrusters models is often sufficient for open-loop simple movement regulation, where no sensors are required.

Yoerger et al. (1990) and Bessa et al. (2013) address the influence of thruster dynamics on the behavior of the underwater vehicles. The authors propose a series of corrective filters to decrease the effect of nonlinearities, and those caused by a deterioration of a thruster performance. They show that these effects can cause not only a loss of performance, but also a limit cycle in response to control for dynamic positioning.

The redundancy management is an important theme of humanoid robotics, or in the domains of manipulation Mansard (2006) and Khalil et al. (2003). The task function approach is used in Flacco et al. (2012) to avoid singularities and saturation of the actuators. Nakamura et al. (1987) addresses the priority that can be attributed to secondary tasks for robot manipulators.

In our case, we use the task function approach to concurrently consider additional constraints on the actuators of a redundant underwater vehicle, in order to remove the effects of thrusters dead zones, parametric uncertainty, to respect the actuators saturation, and to manage the actuation reactivity. For previous work and a more complete

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[2] A. Lasbouygues work is supported by the Labex NUMEV.

https://doi.org/10.1016/j.oceaneng.2017.12.025
Received 13 June 2016; Received in revised form 13 November 2017; Accepted 10 December 2017

Fig. 1. The Jack system.

bibliography on the subject, please refer to Ropars et al. (2015) and the references therein.

The paper is organized as follows. Section 2 introduces the notation, problem statement and presents the system that is used as study case and on which experimental validation is performed. The effects of actuators dead-zone and actuators' characteristic disparity is shown and analyzed. Section 3 exposes our proposition. This solution is analyzed in section 4, and experimental validation is rerouted at Section 5. Section 6 concludes this study and presents the perspective it opens.

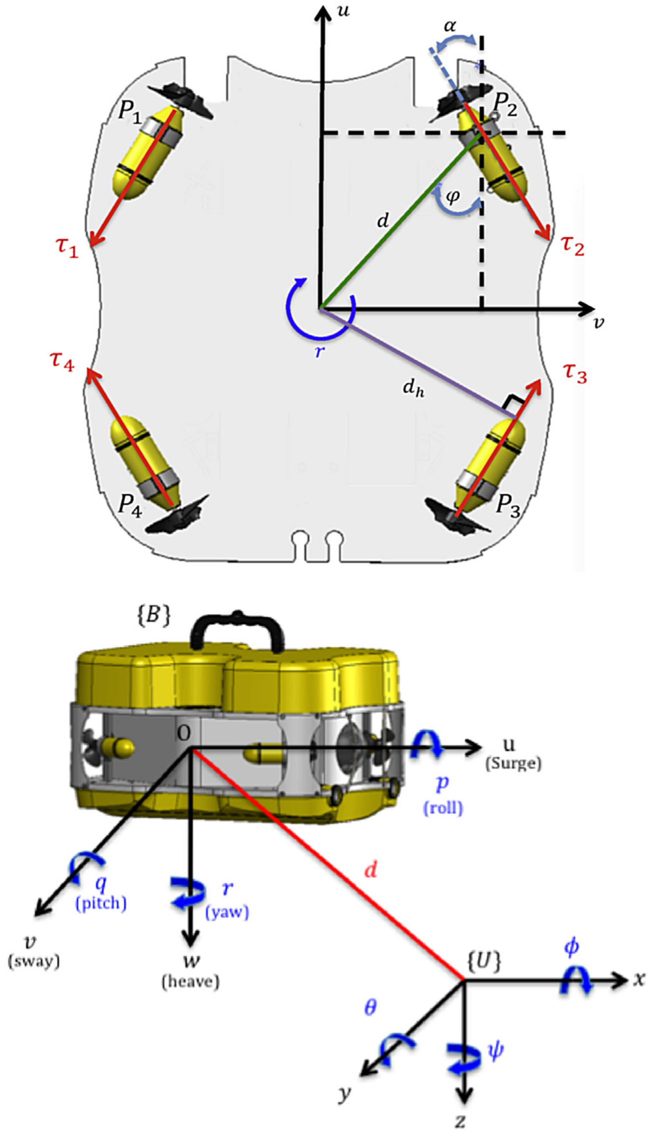

Fig. 2. Notation and frames definition, for Jack.

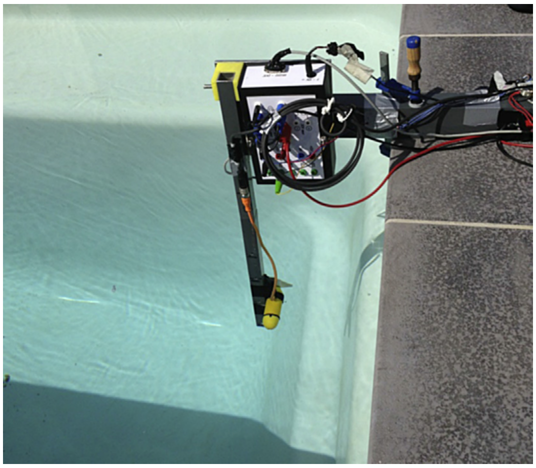

Fig. 3. Notation and frames definition.

2. Problem statement

This study is based on the Remotely Operated Vehicle (ROV), Jack, manufactured by the Ciscrea Company, on which electronic and control architectures has been rebuilt. Fig. 1 shows the system, carrying 6 thrusters able to induce actions on the three components of translation (surge, sway and heave) and two components of rotation (roll and yaw). Only the pitch is not controllable, but naturally stabilized because the buoyancy center is placed over the center of mass (this restoring torque effect is also present in roll).

This study tackles the question of redundancy management of actuation system of Jack and particularly the horizontal actuation system because our robot has 4 thrusters to control 3 degrees of freedom (surge, sway, yaw). As it will be shown in the sequel, the redundancy management will allow for reducing the effect of motors' characteristic disparity, as well as dead-zone effects.

2.1. Notation

In the sequel, 'bold' notation is reserved for vectors and matrices, while scalars are written classically. Let $\{U\}$ be the universal coordinate frame and $\{B\}$ be the body frame. In the sequel, $\boldsymbol{\eta}_U$ expresses the system state in $\{U\}$, $\boldsymbol{\nu}_B$ is the system velocities in $\{B\}$ and $\mathbf{F}_B$ represents forces and torques (provided by the actuation system) w.r.t. $\{B\}$, as stated on Equation (1) and illustrated at Fig. 2.

$$\begin{aligned} \boldsymbol{\eta}_U &= [x, y, z, \phi, \theta, \psi]^T \\ \boldsymbol{\nu}_B &= [u, v, w, p, q, r]^T \\ \mathbf{F}_B &= [F_u, F_v, F_w, \Gamma_p, \Gamma_q, \Gamma_r]^T \end{aligned} \tag{1}$$

Referring to Fig. 2, each of the 4 horizontal actuators (motor + propeller) is mounted on the system with positioning parameters defined w.r.t $\{B\}$, for motor i, defined as the set $[d_{x,i}, d_{y,i}, d_{z,i}, \theta_{m,i}, \psi_{m,i}]^T$.

The system kinematic model is classically taken as:

$$\dot{\boldsymbol{\eta}}_u = \mathbf{R}(\phi, \theta, \psi) \cdot \boldsymbol{\nu}_B \tag{2}$$

where $\mathbf{R}(\phi, \theta, \psi)$ denotes the kinematic relation between velocities expressed in the body frame $\{B\}$ and universal frame $\{U\}$, using Euler angle (ϕ, θ, ψ).