Dynamic Maneuverability Analysis of an Autonomous Underwater Reconfigurable Vehicle

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***Abstract*—Since the development of the first autonomous underwater vehicles, the demanded tasks for subsea operations have become more and more challenging as, for instance, intervention, maintenance and repair of seabed installations, in addition to surveys. As a result of these considerations, the development of Autonomous Underwater Re-configurable Vehicles (AURVs) with the capability of interacting with the surrounding environment and autonomously changing the configuration, according to the task at hand, can represent a real breakthrough in underwater system technologies. A novel formulation for the dynamic maneuverability analysis of an AURV, adapting Yoshikawa's manipulability theory for robotic arms, is proposed.**

***Index Terms*—Marine Robotics, Reconfigurable Drones, AUVs**

I. Introduction

Autonomous Underwater Vehicles (AUVs) featuring intervention capabilities can be the key to push the boundaries of the underwater robotics task variety and still represents one of the most challenging objective of the underwater industry and scientific community. To address this challenge we propose an AUV with the ability to autonomously switch between configurations, depending on the task to accomplish [1].

Autonomous Underwater Re-configurable Vehicles (AURVs) are capable of performing both surveys and inspection/intervention tasks, such as maintenance operations in offshore installations or sample collection in aquaculture or deep-sea mining, with the same effectiveness and efficiency. Driven by these considerations, we have designed an innovative AURV (Fig. 1) capable of efficiently re-configuring its shape, according to the task at hand, spanning from a "survey," slender configuration to a "hovering," stocky configuration. Whereas an exhaustive overview of the mechanical layout has been previously reported in [2], this work introduces a dynamic maneuverability analysis method for underwater vehicles which is applied to the aforementioned robot. In particular, the procedure to carry out a quantitative evaluation of maneuverability is hereby presented, starting from the dynamic model of the underwater vehicle.

Fig. 1. The UNIFI DIEF AURV in the hovering and survey configurations.

The paper structure reflects the procedural workflow. Section II summarizes the research work design guidelines alongside a review of the major exploited theoretical concepts. Section III describes the new dynamic maneuverability formulation while providing the application of this theory to the UNIFI DIEF AURV.

II. AURV Dynamic modeling

The dynamic model of the AURV is reported below in order to get a thorough understanding of the hierarchical steps of the maneuverability analysis. The standard AUV dynamic model [3] (see Eq. 1) has been extended to take into account several configurations of the robot by introducing the joint vector $\boldsymbol{q}$:

$$M(\boldsymbol{\nu},\boldsymbol{q})\dot{\boldsymbol{\nu}} + C(\boldsymbol{\nu},\boldsymbol{q})\boldsymbol{\nu} + D(\boldsymbol{\nu},\boldsymbol{q})\boldsymbol{\nu} + \mathrm{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}(\boldsymbol{u},\boldsymbol{\nu}) \quad (1)$$

where $\boldsymbol{\nu} = [\boldsymbol{\nu}_1\ \boldsymbol{\nu}_2]^T$ indicates the body-fixed frame linear ($\boldsymbol{\nu}_1$) and angular ($\boldsymbol{\nu}_2$) velocities, $M(\boldsymbol{\nu},\boldsymbol{q})$ describes the mass matrix, $C(\boldsymbol{\nu},\boldsymbol{q})$ outlines the centrifugal and Coriolis matrix, $D(\boldsymbol{\nu},\boldsymbol{q})$ reports the damping matrix, $\mathrm{g}(\boldsymbol{\eta})$ are the effects of gravity and buoyancy, and $\boldsymbol{\tau}(\boldsymbol{u},\boldsymbol{\nu})$ delineates the forces and torques acting on the AURV. Furthermore, the generalized forces $\boldsymbol{\tau}(\boldsymbol{u},\boldsymbol{\nu})$, the thrusts carried out by the motors

$\boldsymbol{t}(\boldsymbol{u},\boldsymbol{\nu}) \in \mathbb{R}^m$ ($\boldsymbol{t}$ is a vector collecting the thrusts exerted by the the m motors), and the rotational speed of the motors $\boldsymbol{u} \in \mathbb{R}^m$, are linked by using the following relation:

$$\boldsymbol{\tau}(\boldsymbol{u},\boldsymbol{\nu}) = B(\boldsymbol{q})\boldsymbol{t}(\boldsymbol{u},\boldsymbol{\nu}) \tag{2}$$

where $B(\boldsymbol{q}) \in \mathbb{R}^{6\times m}$ is the Thrust Allocation Matrix (TAM) that depends upon the thruster poses with respect to the vehicle center of gravity.

With regard to the propulsion system [4], the four-quadrant motor characteristic is approximated with the purpose of modeling the relationship between the thrust value t_i and the rotational speed u_i of the thruster:

$$t_i\left(\nu, u_i\right) = d\left(u_i, \mathcal{V}\right)\left[\operatorname{sgn}\left(u_i\right)\left(k u_i^2 - f(p_p, V_{a,i}\right)\right] \tag{3}$$

where k is a coefficient that relates motor thrust and propeller speed at bollard conditions, $f(p_p, V_{a,i})$ is a function depending on the $i-th$ motor advance speed $V_{a,i}$ and the propeller pitch p_p (a construction parameter), and $d\left(u_i, \mathcal{V}\right)$ is the term including in the model the dead-zone boundary values at the voltage supply level $\mathcal{V}$. In the context of this work, a preliminary assumption has been done by neglecting the dead-zone boundary values and the term depending upon the motor advance speed. Driven by these considerations, the Eq. 1 can be simplified as follows:

$$M(\boldsymbol{\nu},\boldsymbol{q})\dot{\boldsymbol{\nu}} + \Gamma(\boldsymbol{\nu},\boldsymbol{q},\boldsymbol{\eta}) = T(\boldsymbol{q})\boldsymbol{u}^2 \tag{4}$$

where $T(\boldsymbol{q}) = kB(\boldsymbol{q})$, and $\Gamma(\boldsymbol{\nu},\boldsymbol{q},\boldsymbol{\eta})$ represent the sum of the non-linear generalized forces applied to the re-configurable vehicle, and $\boldsymbol{u}^2 = \left[\begin{array}{cccc} u_1^2 & u_2^2 & \dots & u_m^2 \end{array}\right]^T$.

III. Dynamic maneuverability formulation

The concept of dynamic maneuverability measurement for AURVs can be defined by adapting the Yoshikawa manipulability approach [5] for robotic arms. Indeed, a quantitative result of the vehicle ability to move along its several degrees of freedom, by taking into account the vehicle system dynamics, is proposed in this section. In particular, the problem of estimating the quasi-maximum values of the AURV body accelerations given the quadratic expression of the thruster rotational speeds, has been addressed by the authors. Thus, the set of all propeller rotational speeds, at the input to the dynamic system, can be formulated as:

$$\left(\boldsymbol{u}^2\right)^T \boldsymbol{u}^2 = 1 \tag{5}$$

Additionally, by combining the overall AURV dynamic model (Eq. 4) with the previous input equation (Eq. 5), the dynamic maneuverability ellipsoid is obtained, as reported below (Eq. 6).

$$(\dot{\boldsymbol{\nu}} + M^{-1}\Gamma)^T (T^{\dagger}M)^T (T^{\dagger}M)(\dot{\boldsymbol{\nu}} + M^{-1}\Gamma) = 1 \tag{6}$$

From such a mathematical equation, it can clearly be observed that any acceleration due to nonlinear forces $\Gamma(\boldsymbol{\nu},\boldsymbol{q},\boldsymbol{\eta})$ generates a translation with respect to the center of the ellipsoid.

Finally, the defined formulation has been employed to carry out a quantitative maneuverability computation for the UNIFI DIEF AURV in the two extreme configurations, i.e. the survey one and the hovering one. More in detail, by normalizing $\boldsymbol{u}$ with respect of the maximum rotational speed in Eq. 5, the achieved dynamic maneuverability ellipsoids are shown in Fig. 2 (the angular ellipsoids have been omitted for sake of brevity).

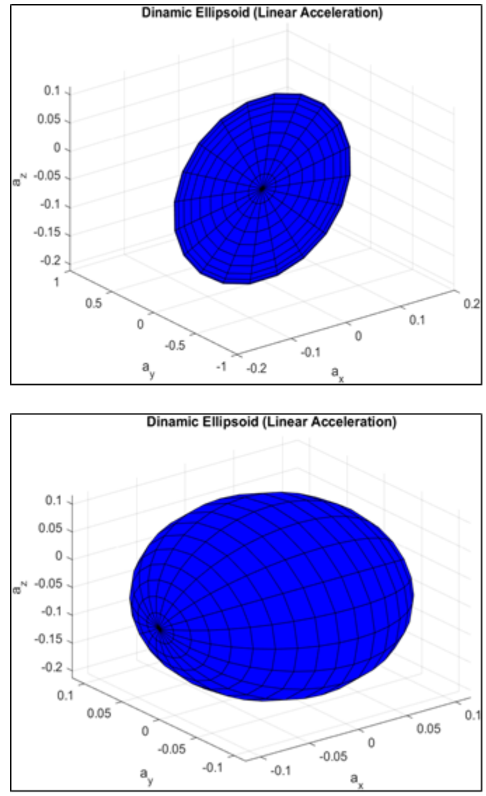

Fig. 2. The estimated linear dynamic ellipsoids for the two distinct configurations of the UNIFI DIEF AURV. As can be seen from the graphs, the linear dynamic ellipsoid turns to a circle in the case of the survey configuration (top figure) since there is not any possible motion on the sway direction; conversely, the hovering configuration (bottom figure) is provided with a maneuverability feature in the three different linear degrees of freedom.

Acknowledgments

This work has been supported by Project SCN00306 SUONO - Safe Underwater Operations iN Oceans funded by the Italian Ministry of Education, University, and Research in the framework of the competitive call on Smart Cities and Communities - Topic on Marine technologies (2014 - 2021).

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