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Redundant and reconfigurable propulsion systems to improve motion capability of underwater vehicles

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ABSTRACT

Inspection of offshore plants or harsh marine environments, requires underwater vehicles with high autonomy, performances and maneuverability. These features are deeply affected by the design of propulsion system. An accurate design of the propulsion system, involves the modelling of the response of propellers. In this work a reconfigurable propulsion layout for an inspection vehicle is presented. Performances of the proposed solution are evaluated and compared respect to the conventional one which is currently installed on benchmark test vehicle (the MARTA AUV from University of Florence). Proposed layout exhibit superior maneuvering performances that should be useful for the inspection of offshore plants and more generally for harsh operational conditions.

1. Introduction

In this work, the applicability of a reconfigurable propulsion layout for underwater vehicles for offshore operations will be investigated. The innovative layout proposed, visible in the scheme of Fig. 1, is characterized by an array of four low cost pivoted thrusters that can be easily customized and optimized with respect to operating and mission profiles. In particular, authors supposed that the angular position of each thruster around its pivot axis, is controlled by a servomotor.

In existing solutions available in literature, such as SmartE AUV, (Meyer et al., 2013; Ehlers et al., 2014), three pivoted thrusters are used to perform a holonomic control of the six degree of freedom of underwater vehicle.

In this proposed study, authors want use four pivoting actuators to control the vehicle motion to improve the maneuverability, the efficiency and the failure robustness with respect to a traditional AUVs or ROVs.

In details, the work is organized as follows:

In Section 2, it's introduced Current State of the Art and definition of a benchmark vehicle and operating scenario.

In Section 3, it's described the design of an actuator unit according to chosen requirements. Description includes preliminary tests and simplified models adopted to identify main features of the prototype in terms of performances and efficiency. In particular Finite Element design of the actuator magnetic joint is explained in Section 4, while preliminary experimental activities to identify actuator performances are described in Section 5. Finally a Virtual Model of the whole system aiming to investigate the potential features of the proposed approach is described in Section 6.

Results in terms of comparison between the proposed innovative solution and the conventional one are finally shown in the last part of this work corresponding to Section 7.

2. Current state of art

This work is based on the experience acquired by authors in the prototyping of hybrid multi-role AUVs (Autonomous Underwater Vehicles) 'TIFONE' (Allotta et al., 2012, 2011, 2015a), and 'MARTA' (Allotta et al., 2015b; ARROWS Project), whose propulsion layout is shown in Fig. 2. In this vehicles, two rear propellers are used for standard-straight navigation and a certain number of tunnel thrusters are devoted to control orientation or to keep the vehicle hovering over an assigned target. Considering the high number of controlled independent actuators (six), fixed pitch propellers are adopted to simplify the control logic. This choice allows to reduce costs. Additional vantages are represented by increased modularity and reliability of the whole vehicle, thanks to use of simple and standard components for all actuated axis.

Usually, the resulting propulsion layout makes possible to control five degree of freedom, which are described according the classical SNAME notation, widely adopted in literature (Fossen, 1994):

- Surge Motion: longitudinal load X is the sum of the thrust delivered by the two rear propellers.

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Adopted symbols

x, y, z	displacements along the three coordinate axis (surge, sway, heave directions)
ϕ, ψ, θ	rotations angle respect to the three axis (roll, pitch, yaw, rotations)
u, v, w	speed along body constrained directions (surge, sway, heave)
X, Y, Z	resultant forces applied on the tree body constrained directions (surge, sway, heave)
K, M, N	resultant torques applied along the three body constrained axis (roll, pitch, yaw, rotations)
τ	vector of resultant forces and torques applied to the vehicle (six components, X, Y, Z, K, M, N)
β	Propeller advance angle
V_a, n	Propeller advance and rotational speed
p,d	Propeller Pitch and Diameter
Q,T	Propeller Torque and Thrust
J	Advance Coefficient
K_T,K_Q	Thrust and Torque Coefficients
C_T,C_Q	Modified (four quadrant) Thrust and Torque Coefficients
A_k,B_k,C_k, D_k	parameters of the formula defining modified Thrust and Torque Coefficients C_T, C_Q
T_{ij}	Thrust delivered in the i-th direction by the j-th thruster, in particular the i-th index should be equal to "p" (thrust projected on the x-y plane) or "c"(thrust component in the z direction, vertical direction); the j-th index identifies the thruster, since in the vehicle are installed four thrusters j should be a number from 1 to 4
ω_i	angular orientation/position of the i-th thruster along his pivot axis
l_{ij}	are the distances between thruster axis respect to a body constrained reference system visible in Fig. 13. In particular the i-th index should be equal to "p" (distance projected on the x-y plane) or "c"(distance in the z direction, vertical direction); the j-th index identifies the thruster, since in the vehicle are installed four thrusters j should be a number from 1 to 4
H_i	maneuverability index in the direction i
V_i	speed of the vehicle in a generic direction i
W_i	corresponding power need to move the vehicle in the i direction

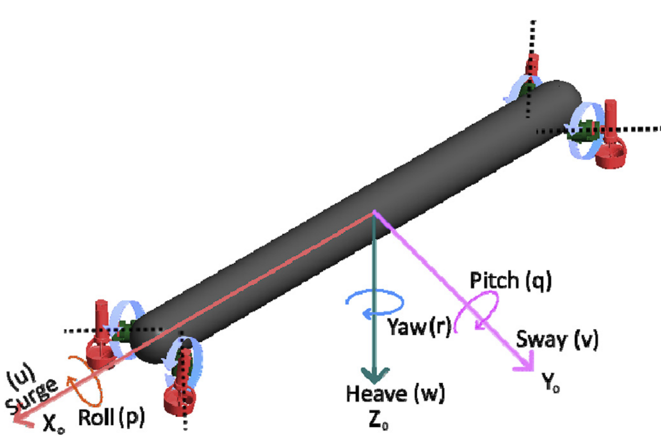


Fig. 1. Example of application with four orientable thrusters with SNAME notation.

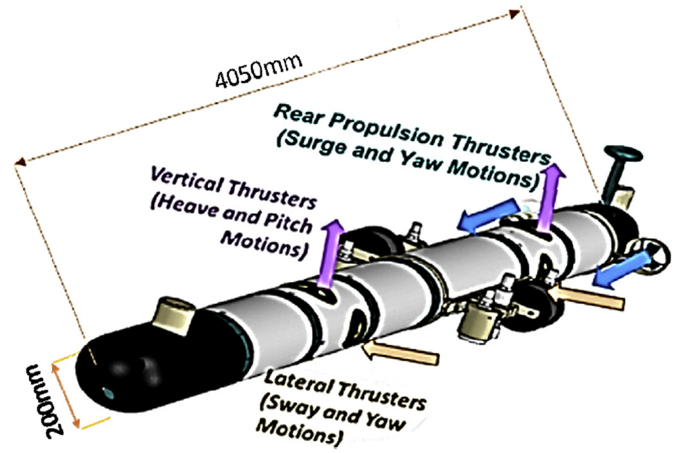


Fig. 2. Marta AUV propulsion layout and corresponding encumbrances.

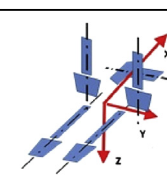
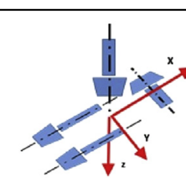
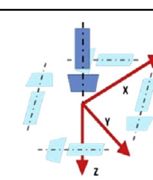
- Sway and Heave: lateral load Y and Z are respectively the sum of the thrust of the two lateral and vertical Tunnel Thrusters.
- Pitch and Yaw rotations: vertical and lateral thrusters respectively control these rotations. Yaw rotation has a redundant actuation, since it can be controlled also using the two rear propellers.
- Roll rotation: usually is the only degree of freedom that is not controlled. The stability of this D.O.F is ensured by an appropriate choice of static weight and buoyancy distributions. Also fins should be used to further stabilize the vehicle respect to roll motions.

Many existing AUVs adopt similar combinations of fixed pitch rear propellers and lateral tunnel thruster to increase vehicle maneuvering. It is possible to cite many examples, such as C-Scout (Curtis et al., 2000), Remus (Stokey et al., 2005), Proteus (Whitney and Smith, 1998), Delphin2 (Phillips et al., 2009) and Folaga (Alvarez et al., 2009).

In this kind of layouts, the actuation of different degrees of freedom is highly decoupled, making quite easy the control of the vehicle. In addition, a wise choice of the propeller rotation sense can reduce the motion disturbances arising from propellers reaction torques. Also an easy controllability is an important requirement for the design of commercial ROVs (Remotely Operated underwater Vehicles), where the vehicle has to be maneuvered by a human operator, with a limited level of additional automation. Some examples of propulsion layouts often adopted on ROVs (or AUVs) are visible in Table 1.

Unfortunately, one of the drawbacks of the propulsion layout adopted on 'MARTA' or similar AUVs is the encumbrances of the propulsion system with respect to the payload. As shown in Fig. 2, the length of the MARTA Vehicle is about 4000 mm (about 18 times bigger with respect to hull diameter). However, the total length of the three propulsion modules is more than 1.2 m. In addition, it should be noticed that over-cited

Table 1
Controlled and Uncontrolled Degree of Freedom for some typical Propulsion Layouts Adopted by commercial ROVS.

			
Surge	Controlled	Controlled	Controlled
Sway	Controlled	Controlled	Controlled
Heave	Controlled	Controlled	Controlled
Roll	Controlled	Not Controlled	Not Controlled
Pitch	Not Controlled	Not Controlled	Not Controlled
Yaw	Controlled	Controlled	Controlled