

A ROBOTIC EQUIPMENT FOR THE GUIDANCE OF A VECTORED THRUSTOR AUV

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1 ABSTRACT

The paper deals with developing a cheap autonomous underwater vehicle, SWAN, Submarine Wobble-free Autonomous Navigator, entrusted of extended manoeuvrability for surveying and docking missions with accurate control, both, of trajectory tracking and of attitude keeping. SWAN belongs to easily transported devices (weigh 30-50 kg, length 1-2 m), capable of travelling at low speed (0.8-1.2 m/s), at proper depth (10-500 m deep), to carry out the chosen task with proper autonomy and without relevant impact on the surroundings.

The currently available AUVs, generally, make use of several propellers, distributed around the body, to achieve the desired mobility with due attitude control. The solution requires the closure of multiple loops between sensors and actuators, highly dependent on dynamics non-linearity and marine surroundings disturbances [1].

The prospected solution considers a properly shaped vehicle to grant minimal drag for lowering power consumption. A single rear propeller has in charge propulsion and manoeuvring. The propeller can suitably be oriented around two axes by, say, a pitch angle (for heaving) and a yaw angle (for veering); the hydrodynamic torque of the screw would generate a twist with roll, surge and sway effects, unless proper balance is provided. The joint path and attitude control is obtained by driving the propeller assembly through a three degrees of freedom parallel kinematics robotic wrist.

The worked-out lay-out consists in a duct-restricted propeller. The duct, further to the pitch and yaw angles, can supply a continuous rotation to counter-act the screw twist or, as case arises, can modify the bent of externally carried fins, so that the AUV attitude is accurately preserved. The paper introduces the generalities of the lay-out and presents example details obtained, for explanatory purposes, by virtual checks on a digital mock-up.

2 INTRODUCTION

Un-tethered underwater vehicles are valuable option for autonomous missions [2,3]. Remotely operated bodies have limited ranges within umbilicals lengths, and manned submarines face risky constraints for due safety, while, both, are expensive set-ups, with supporting trailers and connected facilities. The SWAN submersible,

accordingly, become effective answer, whether cheap and lean arrangements are devised, still assuring good manoeuvrability, with high accuracy in path tracking and attitude keeping. Leanness, today, clashes with behaviour performance, as this is achieved by highly sophisticated propulsion lay-out, based on multiple thrust arrangements assuring the motion of the centroid and around it by independent actuation.

The prospected solution resorts to a single vectored thruster: the combination of heave or veer turn is obtained by modifying the pitch, either, the yaw angles of the screw propeller axis. The perturbing twist needs a balancing torque around the thruster axis, exactly equalising the spin. This action can be generated by counter-rotating vanes or by suitably swinging fins. All in all, the single vectored thruster assures proper manoeuvring capability, as for path tracking as for attitude keeping, on condition that a three degrees of freedom actuator operates to modify its angular bends for the heaving and veering tasks, and, moreover, to supply the twist balance cancelling out the screw torque.

The conceived AUV results very effective, not requiring any thrust redundancy. Moreover, the hydrodynamic shape can be deprived of complex stabilisation wings or blades, avoiding, as well, the resistive effects, since the guiding and balancing actions are fully entrusted to the purposely-actuated equipment, combining propulsion and steering. The merging within a single device of the different corrective actions for path tracking and for attitude keeping simplifies the SWAN controller, at least for a factual choice of the feedback loops in marine surroundings, where varying streams and local flows severely affect the motion of bodies with complex shapes or multiple thrusts.

The innovative setting is made possible by the availability of a robotic wrist, endowed with the three mobilities, according to the above recalled specifications. The mechanism shall face heavy duty engagements, assuring high stiffness and accuracy. These requirements, quite clearly, lead to a parallel kinematics manipulator, namely, a compact wrist with three driving motors solid to the SWAN hull, actuating a merely rotating effector, which carries the combined propulsion and steering device. The

resulting equipment unifies the commands for path tracking and for attitude keeping, properly distinguishing the power supply to the screw propeller through a shaft with an interposed spherical joint, from the steering and compensating rig with three independent actuators (Fig. 1). The presentation shortly outlines the aims of the study, with introductory architectural details of the purposely-conceived robotic wrist and a few hints on the manoeuvring abilities and strategies. The benefits of the prospected solution are suitably assessed, with resort to explanatory examples carried on an integrated digital mock-up, supplying a prototypal virtual test bench for SWAN performance checks, within the forecast operation conditions. The study, further, covers first guesses on how selecting the basic components and assembling the whole lay-out, prioritising the choice of off-the-shelf supplies.

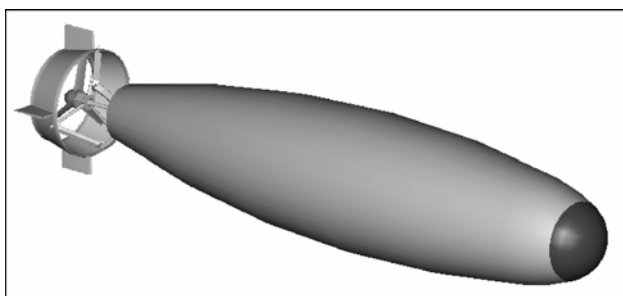


Fig. 1 - The SWAN digital mock-up

3 JOINT PATH-TRACKING AND ATTITUDE-KEEPING

The SWAN design addresses a small and properly shaped outer casing, with overall length around 1.5 m and 50 kg total gross weight. The body, in operation trim, can easily be carried by a couple of men and hauled down from a simple boat. No expensive support is required and every mission is quickly programmed, leaving very little outside impacts and apparent marks. Proper out-fits could modify the operation trim, e.g.: - for shallow water navigation, SWAN can exploit neutral buoyancy set-up, for trajectories properly adapted to the sea bottom profile; - for deep water tasks, SWAN might take in ballast for powerless descents, and progressively jettison it for surfacing.

The applications of this kind of vehicles are fast growing, and example potential fields are:

- scientific: seafloor mapping, geologic or biologic surveying; ocean events monitoring (volcanoes, quakes, etc.);
- industrial: ocean mining and oil prospecting; seabed survey and resource assessment; mapping and monitoring of submerged structures and machines (oil wells, pipelines, etc.); underwater cables inspection;
- military: shallow water mine search and sweeping; coast recognition; enemy areas exploration;
- other fields: maritime traffic acknowledgment; ship hulls inspection; fisheries; entertainment.

Several duties are today accomplished by divers or by remotely operated vehicles. The unmanned solution

acquires interest to lower risks and costs, and to extend the business coverage.

The AUV technology, up now, remains non-fully explored, promising challenge. The underlying technical contributions are mostly appropriate, covering navigation and sensing requirements at a nice level, if, only, proper integration is accomplished. Actually, communication and power supply face critical limitations.

Data transmission (for un-tethered vehicles) exploits acoustic waves and, since the carried energy weakens as frequency increases, long distances are covered at low frequencies, with drawbacks on information density and transducers size; with an AUV, warning or recovery messages only are exchanged, then reception and decoding are comparatively simple.

Electric batteries are standard energy source. Aiming at cheap solutions, lead-acid or Ni-Cd elements are today choice, with weigh, energy density and cycle-life hindrances. Happily, trend to electric cars pushes towards Ag-Zn elements and Lithium-ion or Lithium-polymer cells with higher specific energy (130 Wh/kg, 5 times traditional figures) and prices likely to lower with production rise. This study, thereafter, leaves open several options, depending on the allowed over-all costs and requested mission details.

3.1 Robotic steering and balancing equipment

The SWAN principal innovation lies in the combined fixture, used to shelter and to command the propeller. Basically, two parts shall distinguish, Fig. 2: - the duct, with outer compensation vanes or fins and inner screw propeller; - the wrist, with three co-axial shafts driven by independent motors. The parallel kinematics core element requires accurate analyses, to properly assess the reachable work-space trajectories, free from singularities and, further, assuring suitable transmission figures as for motion (of the counter-rotating vanes), as for force (of the varying slant fins).

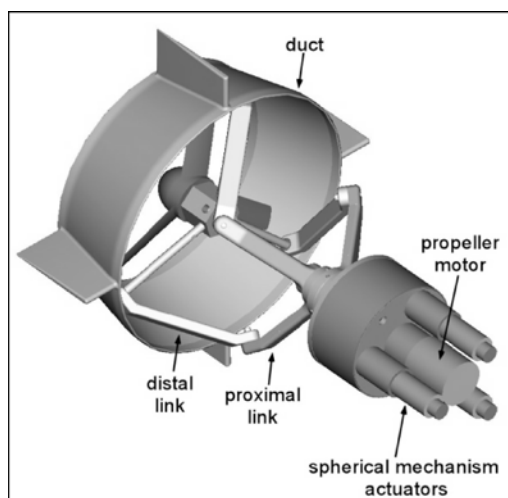


Fig. 2 – The propulsion and navigation fixture

The mechanical architecture of the finally selected robotic fixture splits in the rear part, with three motors and gear-boxes, and the front part, with the three symmetric two-links arms, carrying the propeller shelter. In-between, the motion follows three co-axial shafts. The mechanism makes possible the thruster orientation up to 25° in any direction; for the considered heaving and veering manoeuvres, the angular bends have presently been limited below 15° , to avoid the non-linearity effects on the controlling strategies.

Two alternative settings are possible to compensate the disturbing torque applied by the screw propeller. The wrist can supply a continuous rotary speed to the propeller shelter; if this carries properly shaped vanes, the balancing action is generated through the counter-rotating spin, fed by the three independent motors. The alternative exploits the hydrodynamic coupling of suitable fins, with one tip solid to the AUV hull and whose slant is set (and held) by the wrist twist; the corrective action depends on the surrounding water flow and vanishes if the vehicle relative motion stops.

The power consumption of the steering and balancing equipment is comparatively small, in fact, the thrust is fully supplied by the propeller flow bounded by sheltering duct, and the heave or veer bends require contrasting moments just to withstand the helming efforts. The counter-rotating vanes provide effective spin compensation at low speed (even for docking tasks), while at cruise steady speed, hydrofoils could grant better performance. The appropriate choice has, thus, to be deferred, once the duty-cycles are completely established.

3.2 The 3 d.o.f. steering device

The steering device consists in a spherical parallel mechanism, with three identical chains to move the effector through proximal and a distal links with journal bearings. The axes of all joints converge to the same point: the mechanism centre, Fig. 3. Several architectures with such features are possible, changing the values of the characteristic angular parameters. An accurate analysis, [4], has oriented the development to the specific application. The moving effector, where the propeller shaft and stabilisation fins are mounted, may be oriented inside a conical workspace, which opening depends on the value of the proximal and distal members; as for the rotation about its normal (roll angle), there is virtually no limit, thus every point inside the workspace may be reached with the desired configuration.

The design of the special rigs is outlined in the quoted reference. The quantitative investigation allowed to reach a properly effective parametrical lay-out. While the prototypal construction of the wrist goes on, the study has turned, more specifically to the AUV domain, to look after basic assembly requirements. The reference dynamical model is main reference for selecting the critical operation constraints, either for the structural parts, either for the expected duty capabilities.

These specific data have brought in several up-dating. The need to completely separate the wet zone, where propeller and fins are located, from the dry one, in which

actuators, electronic boards, battery pack and general instrumentation find place, suggested to modify the architecture of the spherical wrist, Figure 3 (a), to the particular lay-out in which all the three actuators have the same revolution axis (b) and may be relocated outside the working space. Moreover, the moving platform is simplified, imposing co-planarity and symmetry of the distal revolute joints axes.

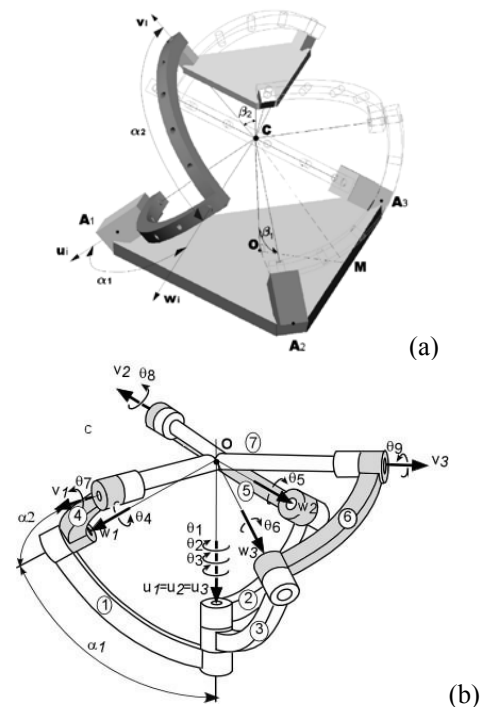


Fig. 3 - The spherical parallel mechanism: general solution (a) and special architecture (b).

The check of the architecture, [4, 5], shows that, in the work domain the dexterity figures are properly balanced and sufficient apart from singularities. This, actually, is main hindrance when parallel kinematics mechanisms are considered, and requires proper assessment during design.

3.3 Balanced vectored-thruster manoeuvring

The AUV navigation is assumed to be planned within earth reference axes, and continuously verified and up-dated with information directly collected from the fixed world surveying. The listed application fields show that an AUV is specially suited for data collection, strictly linked to properly defined targets, thus knowledge refreshing and interactivity are inherent mission specification. On these premises, path tracking and attitude keeping are based on adaptive commands, and require local trim and duty-driven feedback loops.

The prospected vectored thruster equipment has the necessary ductility to match with a wide set of mission-driven tasks, properly adapting the control to the events progression and to surroundings

recognition. Four feedbacks are continuously active, to modify the propeller speed, to select the veer and heave turns and to cancel out any unwanted twist. The correct attitude, indeed, is basic request, to preserve the instrumental setting, with accurate trim on the reference targets. A few prototypal AUVs have already considered the vectored thruster principle, but by experimenting two degrees of freedom propeller commands, faced the bias of the continuous screw disturbance [6, 7].

The architecture based on the innovative robotic wrist provides the additional third mobility and the related regulatory opportunity. To this goal, the equations of motion of the immersed body are written, including the different hydrodynamic effects of the added mass and inertia, and of the drag and lift coefficients of the main body and of the propeller shelter with hydrofoils. The model takes into account the motion of the centroid and around it, and proper feedbacks apply for path tracking and attitude keeping, within the linear approximation of aeronautical angles and loop decoupling.

Both the above recalled balancing strategies are considered. They lead to different hydrofoils, corresponding to alternative design and operation specifications. The availability of comprehensive digital mock-ups, with suitable inclusion of actual running conditions and environmental effects, are worthy aids to compare benefits and drawbacks of the competing options. The ranking of proper choices is, at the present stage, accomplished by means of simulations and virtual tests.

4 PRELIMINARY VIRTUAL CHECKS ASSESSMENTS

The actual advantages of the robotic wrist, to steer and compensate the vectored thruster set-up, are better explained by making use of the results of virtual tests accomplished on the modelled AUV.

The vectored thruster equipping the AUV aims at lower the drag forces and at better guidance abilities for low speed manoeuvres, based on the unified attitude control and propulsion fixture. In the following, the benefits deriving from the option are shown, with constructive hints on the prospected orienting device. The preliminary description and quantification of force and moment supplied by the thruster are needed, for design and development purposes, based on computer simulation.

The resort to a screw propeller causes the simultaneous generation of a thrust component along the propeller axis, \mathbf{T} , and a reactive twist \mathbf{Q}_T that tends to turn the submersible opposite to the propeller rotation. The unwanted effect significantly disturbs the attitude of small vehicles, and the trim actions depend on many, not easily predictable, hydro-dynamical facts. The use of a propeller equipped with two counter-rotating screws would be worthy solution for torpedo-shape AUV, unable, however, to modify the corrective action, for instance, in front of submarine currents or local surges, unless independent controls apply to the two power lines. Moreover, this increases the complexity of the power supply, since both lines requiring adaptive control,

becoming unsuitable for cheap vehicle, as the considered one, since the overall thrust will depend on the balance between the two applied moments. The solution, indeed, provides control capability, only by adopting, both, thrust and torque as case arises along the tracked path.

The prospected solution is, on the contrary, very flexible and simple, since it exploits the rotation about the propeller axis, say the roll to contrast the reactive moment by rotating the propeller duct, with negligible effects on the applied thrust. The purposely-conceived three-degrees-of-freedom wrist, directly actuated through a parallel mechanism, so that independent commands are possible, supplies this additional mobility.

The analytical expressions of thrust vector \mathbf{T} in body frame components T_x , T_y and T_z , are (see Fig. 4):

$$T_x = T \cos(\delta_d) \cos(\delta_r) ;$$

$$T_y = T \cos(\delta_d) \sin(\delta_r) ;$$

$$T_z = T \sin(\delta_d).$$

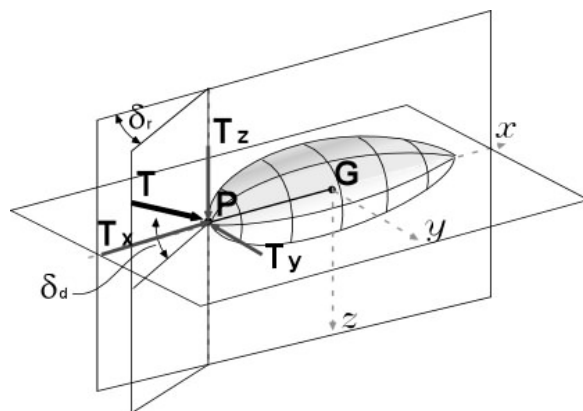


Fig. 4 - Orientation of the thrust

Whether the centre of rotation of the orienting mechanism has an off-set (\overline{PG}) from the centre of gravity, the vectored thruster creates disturbing moments on the AUV, each time the propeller axis does not lay along the body longitudinal axis x ; namely:

$$Q_y = T_z \times (\overline{PG}) ; \quad Q_z = T_y \times (\overline{PG})$$

In fact, the rotation of the screw in the water causes, simultaneously with the thrust force, the application of a reaction torque on the vehicle.

The effect of the reaction moment \mathbf{Q}_T causes the AUV to rotate around its own longitudinal axis with a loss of control on the vehicle attitude. To eliminate this disturbing effect, the third degree of freedom of the orienting device, the rotation about the propeller axis, is used to generate a corrective torque revolving the thruster duct. Since the spherical mechanism takes care both about the orientation of the propeller

and the rotation of the tunnel, the rotation axis of the screw always coincides with the rotation axis of the duct so the control system can annihilate the propulsion torque Q_d without generating any non-desired effect.

The non-linear behaviour of the thruster has been modelled as suggested by Fossen and al. in landmark papers [8, 9 and 10].

4.1 Simulation results

The assessment of the SWAN behaviour has been performed by mean of a simulation program built in *Matlab-Simulink*[®] environment. Figure 5 shows the simulation results of performing a spiral descent down to a depth of -6 meters with the vehicle moving at a constant speed of 1 m/s and with the roll (θ) offset compensation in order to have a level flight throughout the mission.

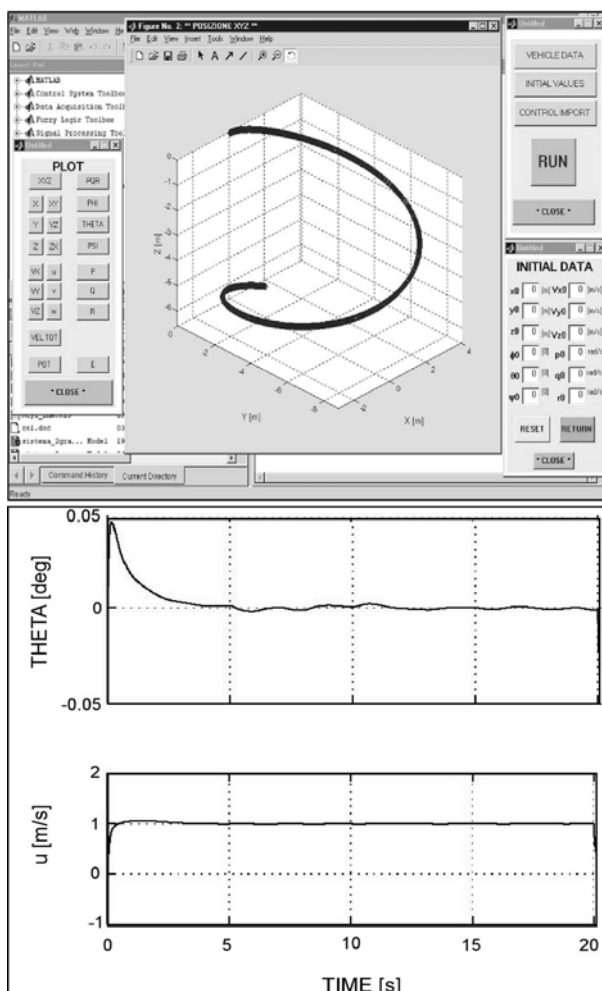


Fig. 5 – The vehicle simulated trajectory for the descent mission

The simulation results show that the AUV equipped with the proposed system for the combined propulsion and navigation duties has good performance and may control the submersible trim during the mission duration. Depending on the submersible shape and mass

distribution it is possible to identify two different cases for the roll error behaviour. For non-neutral buoyant vehicles, i.e. vehicles with non-coincident Centre of Gravity (CoG) and Centre of Buoyancy (CoB), the twist torque exerted by the propeller may be compensated by the restoring moment due to body weight and displacement; as result these vehicle move with constant roll offset. On the other hand, neutrally buoyant AUVs cannot oppose to this action and go on following the planned path with no limit on the roll error reaching uncontrollable configurations.

From these arguments it is clear that the presence of a correcting system able to re-equilibrate the vehicle trim is necessary to control man-portable, low mass AUVs like the one here described.

5 CONCLUSIONS AND FURTHER WORK

The presented work deals with the design and simulation of a new concept AUV, the SWAN, equipped with a joint propulsion and guidance system that allows better control at low speed manoeuvring. The steering system supports the development of small and cheap vehicles, which can be used for many purposes, scientific, industrial, military and other fields, without the need of particular support vessel having high operational costs.

Moreover, the lack of hydrodynamic appendages for guidance purposes consents to reduce the total drag of the vehicle and, thus, the power consumption increasing the mission duration.

A simulation code has been developed in order to preliminary assess the AUV behaviour in real world operational conditions.

The analysis results show that the system satisfies the control requirements and the building of a mock-up may help to test the performance in underwater environment.

The third degree of freedom, used to correct the roll error due to the reactive torque of the screw, looks satisfactory to obtain completely controllable AUV.

Further work will be carried out in order to create a fully comprehensive simulation tool, to be used to assess the dynamic performance of the system. Meanwhile, the control strategy of the vectored thruster underwater vehicle has to be developed, with due account of the inherent non-linear behaviour along with deep- and shallow-water missions.

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