An Advanced Guidance & Control System for an Unmanned Vessel with Azimuthal Thrusters

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Synopsis

The proposed paper presents the design and development of the combined guidance & control strategies for the autonomous navigation of an unmanned vessel characterized by azimuth-based thrust architecture. Autonomous Marine Vehicles (AMVs) are consolidates technological tools commonly employed for different tasks such as exploration, sampling and intervention. With the final aim of autonomous shipping, the capabilities of AMVs have to be migrated and adapted towards the reliable and safe control of commercial-like unmanned vessel, that are taking place thanks to a number of technological research projects. The employment of new concept hulls and thrust configurations, as for instance Small Waterplane Area Twin Hull (SWATH) combined with Azimuthal propulsion (common propeller-based thruster with the capability of 360○ rotation around the vertical axis), requires robust guidance techniques to provide precise and reliable motion control during navigation. The paper proposes a dual-loop guidance & control scheme able to provide advanced navigation capabilities. In particular, the inner control loop, devoted to the actuation of the azimuthal thrusters, allows the tracking of reference course angle (namely the autopilot). Such a control loop is characterized by a modified PID regulation scheme, where a novel adaptive derivative component is inserted in order to improve the convergence curve towards the required course reference. The outer guidance loop, based on Lyapunov/virtual-target approach, allows the vessel to track generic desired paths, thus enhancing the autonomous navigation capabilities also in constrained environments. The paper will provide a deep design & analysis approach for the developed techniques, as well as simulation results of the combined guidance & control scheme, proving the reliability of the proposed approach in different operative conditions. Experimental results will be provided, depending on the availability of the actual autonomous vessel (currently under final development/test phases and related to the specific project activities).

Keywords: Autonomous Guidance, Azimuth Control, USV

1 Introduction

Intelligent vehicles are rapidly taking place in commercial and societal scenarios, such as autonomous cars and flying drones. In the last 50 years there have been a lot of efforts to create and improve intelligent marine agents capable of autonomously navigate on and below the water surface. If in the beginning military goals steered the research and development of such machines, the exploitation of these technological devices has rapidly turned towards civilian applications. Extensive observation and exploration of unknowns marine areas require long range guidance and navigation capabilities as well as robust sea keeping capabilities in order to face severe sea and weather conditions. Environmental sampling and data gathering operations can avail of the employment of autonomous agents thanks to their intrinsic motion precision and capability of operating multiple sensors at the same time, thus allowing to collect high-dimension geo-referenced multi-spectral data. Autonomous marine systems can also be employed in intervention scenarios where the exploitation of remote robotic systems enhances the overall

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safety, keeping the human personnel far from the dangerous scenarios.
Advanced autonomous capabilities are achieved thanks to the continuous research, design and development of suitable techniques for automatic navigation, guidance and control operations, as well as the exploitation of cutting-edge technological results such as new materials, high-performance actuators and accurate sensors.
Navigation guidance and control (NGC) systems represent a consolidated topic in marine robotics and many different techniques have been proposed in the literature. Potential of line-of-sight methods to solve under-actuated control problems (related to path following and maneuvering) are discussed in Pettersen (2015); a complete integral line-of-sight approach is applied to an under-actuated robot in Caharija et al. (2016), presenting all aspects, from theory to simulation and experimental validation.
On the other hand, experimental results obtained on an over-actuated USV capable of omni-directional motion demonstrated a suitable behaviour for the developed NGC Nađ et al. (2015). A cascade structure is combined with the classical sliding mode control in McNinch and Ashrafıuon (2011), in order to achieve required performance (e.g. minimum tracking error, time or energy). A neural learning control approach is applied in Dai et al. (2016) to a marine surface vessel whose accurate dynamics could not be a priori obtained; this strategy is demonstrated through simulation studies.
Given the importance of robot cooperation, as well as the strengthening of single vehicle NGC systems, many research has been conducted on the development multi-agent frameworks. A virtual-target approach for path following is exploited to perform vehicle following in Bibuli et al. (2012), while the same virtual-target technique is combined with formation control to drive an entire swarm of cooperative robots in Bibuli et al. (2014).
The challenge of keeping a marine platform in a moving triangular formation with respect to other two leader vehicles is faced in Soares et al. (2013), where a range-only formation control is employed. A fleet of robotic kayaks is exploited in Mahacek et al. (2012) for patrolling: whenever a threatening boat approaches the monitored area, robots establish a barrier between the ship and the protected area.

With the aim of long range and extended duration autonomous operations, particular care is brought on the most suitable platform for the required operations. Usually, on one side the problem of motion efficiency and low energy consumption are faced, while on the other hand payload capability and sea keeping robustness have to be taken into account. A good trade-off among the different constraints related to the platform choice is the employment of the so called SWATH architecture; the term SWATH stand for Small Water-plane Area Twin Hull, identifying that kind of marine platforms characterized by a double hull structure (catamaran like); each hull is composed by an underwater element, which contains batteries, payload, ballast tanks and that provides buoyancy, and a vertical strut, supporting the main deck above the surface, characterized by a hydrofoil profile in such a way to minimize the surge drag.
CNR is the coordinator of the Italian Flagship Project RITMARE RITMARE (2015), as well as partner in the Regional Project PERMARE, where the design and development, optimization and hydrodynamic characterization are faced for advanced SWATH-like autonomous platforms, combined with azimuthal type thrusters, that have the goal of launching and recovering other autonomous vehicles (gliders, ROVs, AUVs. . .) as well as able to gather environmental data. To reach such a goal and to effectively exploit the capabilities of such systems, an intensive effort has to be done in the research and implementation of efficient guidance and control schemes in order to exploit at best the propulsive and sea keeping capabilities of platforms.
As already known and demonstrated in literature Zaghi et al. (2015), the SWATH model has acknowledged advantages, such as a natural platform stability also at a relatively high speed, combined to an effective wave disturbance rejection, a remarkable sea keeping property and the capability to operate in very shallow waters.
Some of the works in the field, such as Brizzolara et al. (2012), focused on hydrodynamic optimization and design methods to obtain increasingly more effective SWATH-like platforms; authors of Kitts et al. (2012) described the employment of an automatically guided robotic SWATH vessel able to conduct shallow-water bathymetry, thus providing a stable platform suitable for scientific surveys. A couple of vehicles belonging to the SWATH family is presented in Brizzolara et al. (2011), namely: i) a small ASV with SWATH hull for transportation, launch and recovery of medium sized AUVs; and ii) a concept design of a marine vehicle capable of very high speed and long duration, as well as suitable to face relatively rough sea state. Specifically dealing with propulsion systems, many research has been conducted relatively to the optimal control allocation: ideally, the objectives consist in minimizing power consumption and mechanical wear, while fulfilling other physical constraints (e.g. forbidden zones and thruster limitations). The mentioned optimization problem can be solved by employing different techniques; authors of Johansen et al. (2008) proposed a problem re-formulation allowing to exploit multi-parametric quadratic programming. In Cristofaro and Johansen (2014) a control allocation system that actively exploits input redundancy in order to identify and isolate relevant faults is described. Complete and interesting surveys of the employed control allocation strategies both in the marine environment and within other contexts are provided in Fossen et al. (2009) and Johansen and Fossen (2013).

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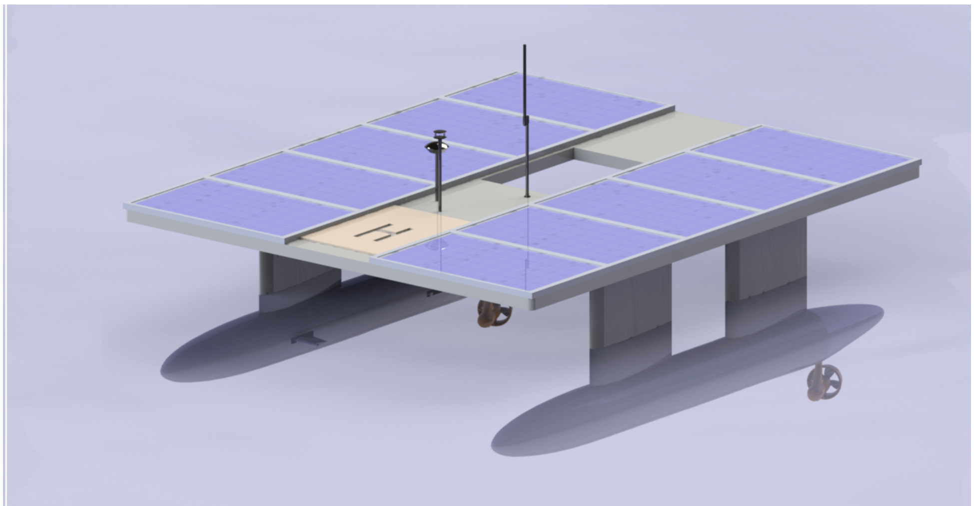

Figure 1: Rendering of the SWATH platform.

The problem of avoiding singular configurations of azimuthal thrusters is faced in Scibilia and Skjetne (2012): such configurations can cause poor maneuverability and temporary loss of controllability and this situation can be recovered very slowly, since azimuth angles of the vessel thrusters can be changed only slowly. Hence an approach based on future predictions of the system behavior is used, allowing to find the current optimal control action. A sequential quadratic programming approach is proposed in Johansen et al. (2004), aiming at minimizing the use of control effort (or power) subject to actuator rate and position constraints; the additional objective of singularity avoidance is also considered.
The paper is organized as follows: Section 2 describes the mathematical modeling of the framework, highlighting the dynamical properties of the autonomous systems; Section 3 reports the envisioned framework describing in details the development of the azimuthal thruster control needed to obtain a precise automatic course-keeping system and the implementation path-following guidance system allowing automatic navigation along preplanned geo-referenced trajectories. Simulation results of both control and guidance systems are reported in Section 4 and final conclusion with future improvements are discussed in Section 5.

2 SWATH-USV Modeling

This section reports the definition and description of the kinematic and dynamic modeling of the autonomous SWATH platform. As depicted in Fig. 1, the platform is characterized by two twin hulls, each one equipped with an aft-mounted azimuthal thruster capable of a complete 360° rotation allowing thrust generation in all desired directions. The platform is 5 m long and 4 m wide, for a total weight of about 1600 Kg, of which 600 Kg of payload.
Despite the full directionality of the azimuthal thruster, the installation of the thrusters in the aft section of the hulls does not provide a full actuation (i.e. capability of generate independent motion along the three horizontal degrees of freedom: surge, sway, yaw); for such a reason the design of suitable guidance and control schemes has an increased complexity and advanced regulation techniques have to be employed.
Given the dimensions and masses of the platform, all the fundamental component dynamics have to be considered; first of all a modeling of the azimuthal thruster system is considered and defined as follows:

$$\dot{F}^*_{\%} = k_F\left(F^*_{\%} - F^*_r\right) \quad (1)$$
$$F^* = a_F F^{*2}_{\%} + b_F F^*_{\%} + c_F \quad (2)$$
$$\dot{\alpha} = k_\alpha\left(\alpha - \alpha_r\right) \quad (3)$$

where eq. (1) describes the linear dynamics (characterized by the parameter k_F) of the thrust force with F^*_r being the desired force percentage (of the maximum available thrust provided by the motor) and $F^*_{\%}$ the actual force percentage; the $*$ symbol indicates left or right thruster, $* = \{L,R\}$. The actual real force is then computed by a quadratic mapping, given by eq. (2). The rotational dynamics of the thruster is modeled by eq. (3) describing the linear behavior provided by the hardware driver that allows the actual thruster angle α to track the desired reference position α_r (the dynamics is characterized by the parameter k_α).
Following the procedure developed in Caccia et al. (2008), the dynamics modeling of an autonomous platform can be identified on the basis of a *practical* model, where *practical* basically stands for consistent, from the point of

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view of the degree of accuracy, with the precision in terms of noise and sampling rate of the measurements provided by the proprio-ceptive sensors available onboard the platform, i.e. GNSS (Global Navigation Satellite System) and AHRS (Attitude and Heading Reference System). In particular, a set of steady-state and zig-zag maneuvers can performed in order to identify the vehicle drag and inertia parameters. Given the complex logistics due to high dimensions and weight of the SWATH platform, the identification procedure has been initially based on a numerical estimation, obtained by means of software for 3D design, mechanical calculation and CFD (Computational Fluido-Dynamics). A general theoretical model of the vehicle hydrodynamics has been considered and simplifications have been performed on the basis of reasonable assumptions and the consistency and quality of the parameter estimations. In the near future, a practical identification phase is planned in order to validate the numerical results and refine the dynamics modeling. Furthermore, given the available data and the operative speed values of the platform, the 3 horizontal degrees o freedom can be considered independent and thus the following 3 uncoupled dynamics equations are identified:

$$m\,\dot{u}_r = -k_u u_r|u_r| + b_u f_u \tag{4}$$
$$m\,\dot{v}_r = -k_v v_r|v_r| + b_v f_v \tag{5}$$
$$I_r\,\dot{r} = -k_r r|r| + b_r \tau_r \tag{6}$$

where m is the mass of the platform (considered in the identification phase equal to 1500 Kg), I_r is the moment of inertia along the z-axis (equal to 5125 $Kg\,m^2$); k_* values represent the quadratic drag coefficients. The values f_* and τ_* are the applied forces and torques with b_* values as multiplicative input coefficients. All k_* and b_* values are positive by definition.

The force values are computed by combining the actual thrust and direction components as follows:

$$f_U = F^L\cos(-\alpha^L) + F^R\cos(-\alpha^R) \tag{7}$$
$$f_v = F^L\sin(-\alpha^L) + F^R\sin(-\alpha^R) \tag{8}$$
$$\tau_r = P_x^L F^L sin(-\alpha^L) - P_y^L F^L cos(-\alpha^L) + P_x^R F^R sin(-\alpha^R) - P_y^R F^R cos(-\alpha^R) \tag{9}$$

considering the α^* angles with value equal to zero when the thruster is aft-oriented; (P_x^L, P_y^L) and (P_x^R, P_y^R) are the local horizontal mounting positions of the thrusters with respect to the platform barycenter.

At the current stage, external disturbances are not considered yet and they will be included in the model in the next study advancement.

For the kinematic modeling, two reference frames are considered: an inertial, earth-fixed frame $< e >$, where position and orientation $[x\, y\, \psi]$ of the vessel are usually expressed, and a body-fixed frame $< b >$, where surge and sway velocities ($[u\, v]$ absolute, $[u_r\, v_r]$ with respect to the water) and yaw rate r are represented. Denoting with $[x_c\, y_c]^T$ the horizontal sea current components (vertical effect of sea motion can be neglected, only horizontal motion is treated), the body-fixed absolute velocity and velocity with respect to the water are related by:

$$u = u_r + \dot{x}_C\cos\psi + \dot{y}_C\sin\psi \tag{10}$$
$$v = v_r - \dot{x}_C\sin\psi + \dot{y}_C\cos\psi \tag{11}$$
$$\tag{12}$$

and the vehicle kinematics is usually expressed in the earth-fixed frame $< e >$ (with x-axis pointing in the North direction, y-axis pointing in the East direction and z-axis pointing downward) as:

$$\dot{x} = u_r\cos\psi - v_r\sin\psi + \dot{x}_c \tag{13}$$
$$\dot{y} = u_r\sin\psi + v_r\cos\psi + \dot{y}_c \tag{14}$$
$$\dot{\psi} = r \tag{15}$$

relating vehicle speed in the earth-fixed and body-fixed frames.

3 Architecture for Automatic Operations

The automatic capabilities of the unmanned vessel are achieved by means of the implementation of suitable guidance and control schemes. In particular, a nested modular architecture is designed in such a way that:

- an inner control system is devoted to the orientation regulation, i.e. the tracking of the desired course profile by generating proper force reference signals;
- the outer guidance loop is responsible of driving the platform along predefined geo-referenced paths by means of the generation of a suitable course reference profile.

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This section describes the details of the control system devoted to the thruster driving, obtained through the development of a modified PD (Proportional-Derivative) control scheme where an adaptive law is applied to the derivative component, in such a way limit overshoot behavior while maintaining good performance during tracking transitions.
In the second part of the section, a robust Lyapunov-based guidance approach is employed, allowing the platform to automatically navigate along a preplanned path.

3.1 Thrust control

The task of driving the autonomous platform, towards a desired course (i.e. orientation with respect to the North) at a predefined speed profile, requires the implementation of a suitable control scheme capable of satisfying performance requirement while at the same time maintaining navigation smoothness; this latter issue is of interest in order to reduce power consumption and mechanical stress, but it is also related to navigation comfort (if the final target is autonomous shipping for human transportation) or data quality (collected data could be affected by abrupt maneuvers or jerky motion).
The overall thrust control scheme couples two sub-systems: one related to the surge (speed of advance) control in order to track a predefined speed profile and another to manage the position control of the azimuth devices in order to provide thrust in the required direction to steer the platform towards the desired course.
Regarding the speed control, a very simple regulation scheme has been employed in this framework (this was not the main focus of the research activity, thus a very simple solution has been implemented for the sake of completeness). The speed control relies on the following regulation law:

$$F_r^* = k_{p_u} e_u + k_{d_u} \dot{e}_u + k_{i_u} \int e_u dt \qquad , \qquad e_u = u_r - u \tag{16}$$

where e is the speed error given by the difference between the reference speed u_r and the actual one u; k_{p_u}, k_{d_u} and k_{i_u} are the proportional, derivative and integral gains respectively. The computed force percentage is then applied to both the thrusters, $* = (L,R)$.

The course control is of more interest from the application perspective, thus more effort has been put into play in order to generate an orientation control scheme able to guarantee good driving performance, while at the same time offering a smooth and jerk-free motion. This control system relies on a modified PD (Proportional-Derivative) scheme where an adaptive derivative gain is embedded; the effect of this variable gain is to preserve the performance of the control effort, but reducing the overshoot effect when reaching the reference value. The course control law is given by the following formula:

$$\tau_r = k_{p_r} e_\psi + k_{d_r}(e_\psi)\dot{e}_\psi \qquad , \qquad e_\psi = \psi_r - \psi \tag{17}$$

where e_ψ is the course error, k_{p_r} is the proportional gain (chosen to be $k_p > 0$) and k_{d_r} is the derivative gain which is function of the course error in order to adapt its value to enhance the tracking performance and varying its value between zero and a maximum value $0 \leq K_d(e_\psi) \leq k_a$. The adaptation law for the derivative coefficient is defined by:

$$k_{d_r}(e_\psi) = \begin{cases} k_a \cos\left(|e_\psi| \frac{\pi}{2\psi_a}\right) & , \quad |e_\psi| \leq \psi_a \\ 0 & , \quad |e_\psi| > \psi_a \end{cases} \tag{18}$$

which acts as a gain smoothing function, continuously rising the derivative coefficient value from zero to k_a when the absolute value of the orientation error $|e_\psi|$ is within the range $[0; \psi_a]$. The derivative component of the controller acts as a braking steer effect slowing down the convergence rate to the reference target. For this reason the braking effect is activated only in proximity of the reference target through the adaptive gain $k_{d_r}(e_\psi)$. The control torque τ_r is then mapped into a proper azimuthal angle, providing the required steering effort. Fig. 2 reports the derivative gain function showing the value of the coefficient in function of the orientation error.

The proof of the control system stability is obtained considering the orientation dynamics equations:

$$\begin{cases} \dot{\psi} &= r \\ \dot{r} &= -r\frac{k_r|r|}{I_r} + \frac{b_r}{I_r}\tau_r \end{cases} \tag{19}$$

and substituting the control law 17 obtaining:

$$\begin{cases} \dot{\psi} &= r \\ \dot{r} &= -\tilde{a}_r r - \tilde{b}_r \psi \end{cases} \tag{20}$$

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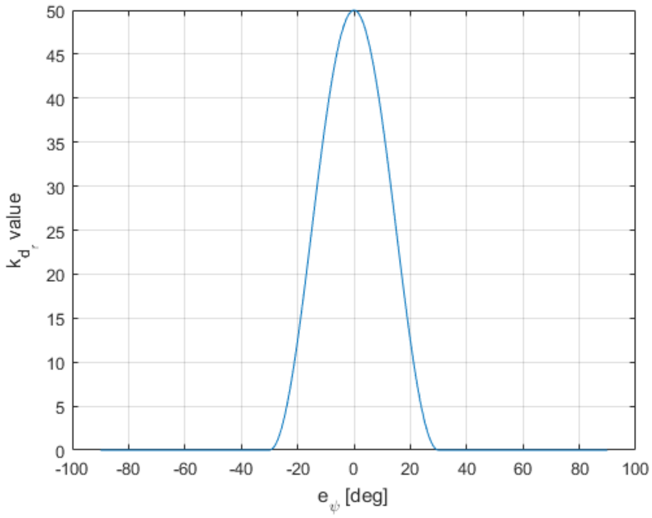

Figure 2: The adaptive derivative coefficient function.

with $\tilde{a}_r = \frac{k_r|r|+b_r k_d(e_\psi)}{I_r}$ and $\tilde{b}_r = \frac{b_r k_p}{I_r}$.
Applying the *Variable Gradient Method*, described in Khalil (2002), it is possible to define a suitable Lyapunov function

$$V = \frac{1}{2}[\psi \ \ r]\begin{bmatrix} \tilde{a}_r\gamma+\tilde{b}_r\delta & \gamma \\ \gamma & \delta \end{bmatrix}\begin{bmatrix} \psi \\ r \end{bmatrix} > 0 \tag{21}$$

with parameters chosen in such a way to comply with the constraints: $\delta > 0$ and $0 < \gamma < \delta\tilde{a}$. Being $k_p > 0$ and $0 \leq k_d(e_\psi) \leq k_a$, $\tilde{a}_r$ and $\tilde{b}_r$ positive values by definition, then computing the time derivative of V the following form is obtained:

$$\dot{V} = -(\tilde{a}\delta - \gamma)r^2 - \tilde{b}\gamma\psi^2 < 0 \tag{22}$$

which being negative defined yield, in virtue of the Lyapunov Theorem, to the asymptotic stability of the system. (Note: the extended stability proof is currently being written and will be available soon on Journal publication).

3.2 Guidance

The aim of automatically drive the SWATH platform on preplanned geo-referenced trajectories is realized through the implementation of an advanced guidance system capable of properly steering the vehicle towards and along the desired reference, on the basis of the current position and velocity sensing. The general idea is to rely on a consolidated solution, successfully employed on marine robot control systems, with the guidance module generating a suitable course signal to be fed to the underlying thrust control (described in the previous section).
The guidance system relies on the idea proposed in Bibuli et al. (2009); assuming the vehicle's motion restricted to the horizontal plane, the task consists in the zeroing of both the position error vector $\underline{d}$, i.e. the distance between the vehicle and the virtual target attached to the *Serret-Frenet* frame $< f >$, and the orientation error $\beta = \psi - \psi_f$, where ψ and ψ_f are the vehicle's direction of motion and local path tangent respectively, expressed with respect to the earth-fixed reference frame $< w >$.
Following the geometrical and kinematical analysis carried out in Bibuli et al. (2009), the distance error model, expressed with respect to the frame $< f >$, has the following form:

$$\begin{cases} \dot{\rho} = (c_c\,\nu - 1)\,\dot{s} + U\cos\beta \\ \dot{\nu} = -c_c\,\dot{s}\,\rho + U\sin\beta \end{cases} \tag{23}$$

In order to solve the path-following problem for a single-vehicle system, the aim is to develop a proper approach angle function ψ^*, designed to reduce the linear error components (ρ and ν) to zero. The desired angle ψ^* is a function of the cross-track error ν summed with the local path tangent, thus $\psi^* = \psi_f + \varphi(\nu)$, where the function $\varphi(\nu)$ is required to satisfy the following constraints:

$$|\varphi(\nu)| < \frac{\pi}{2} \quad ; \quad \nu\varphi(\nu) \leq 0 \quad ; \quad \varphi(0) = 0$$

Relying on a low level controller, providing an auto-heading regulator capable of tracking desired orientation profiles, it can be stated that considering the candidate Lyapunov function $V_\psi = \frac{1}{2}(\psi - \psi^*)^2$, the low level controller

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provides a behavior such that $\dot{V}_\psi \leq 0$, i.e. the vehicle orientation converges to the desired angle $\psi \to \psi^*$ and it can be rewritten as $\beta \to \varphi(\nu)$. Moreover it's worth noticing that when $\dot{V}_\psi = 0$, an invariant set is defined, in which the condition $\beta = \varphi(\nu)$ holds. The task of the path-following controller design is achieved by the definition of the Lyapunov function $V = \frac{1}{2}(\rho^2 + \nu^2)$; computing the time derivative of the function V, the following expression is obtained:

$$\dot{V} = \rho\dot{\rho} + \nu\dot{\nu} = -\rho\dot{s} + \rho U \cos\beta + -\nu U \sin\beta = \dot{V}_\rho + \dot{V}_\nu$$

substituting $\dot{\rho}$ and $\dot{\nu}$ with the equation system (23) and defining $\dot{V}_\rho = -\rho\dot{s} + \rho U \cos\varphi(\nu)$ and $\dot{V}_\nu = -\nu U \sin\varphi(\nu)$. The speed of the reference frame $\dot{s}$, i.e. the velocity of the virtual target moving along the path, can be used as an additional control variable. Imposing

$$\dot{s}^* = K_\rho \rho + U \cos\beta \tag{24}$$

as the desired virtual target speed, where K_ρ is a tunable controller parameter, the function $\dot{V}_\rho$ assumes the negative form $\dot{V}_\rho = -K_\rho \nu^2 \leq 0$. About $\dot{V}_\nu$, recalling the above-mentioned assumption on the attraction to the invariant set defined by $\dot{V}_\psi = 0$, β can be substituted by $\varphi(\nu)$, obtaining $\dot{V}_\nu = \nu U \sin\varphi(\nu)$. Selecting the function $\varphi(\nu)$ as

$$\varphi(\nu) = -\psi_a \tanh(K_\nu \nu) \tag{25}$$

with K_ν as a tunable controller parameter and ψ_a the maximum approach angle with respect to the local tangent ψ_f, the term $\nu U \sin\varphi(\nu)$ is ≤ 0 because of the assumption made on the function $\varphi(\nu)$.
Being the terms $\dot{V}_\rho$ and $\dot{V}_\nu \leq 0$, thus entailing $\dot{V} \leq 0$, the global asymptotic stability for the path-following guidance system is proven.

4 Simulation Results

A number of simulation runs has been carried out in order to, first of all, verify the correctness of the approach obtaining reliable results. Then an extensive parameter set selection and tuning has been executed to find the optimal setting of both the control and guidance modules.
Firstly, the thrust and course control system is put under test requiring the platform to track a course at 90 degrees (with respect to the North, i.e. Eastward), starting from a course of 0 degrees. The result is shown in Fig. 3 reporting the motion of the vehicle driven by control system. The plot depicts the comparison between the motion generated by the proposed adaptive PD control and two standard control schemes, P and PD respectively. As it can be noticed, the P control scheme generates an oscillatory transient that takes quite a long time to settle to the reference value; on the opposite, the PD scheme generates a smooth motion, but the presence of a constant "braking" (derivative) contribution turn into a very slow convergence, with a longer space traveled by the vehicle until the target course is reached. The proposed adaptive PD control exhibits the fast converge rate (fast turn phase) with a smooth and overshoot-free settling to the the reference course value. The same conclusions can be observed in the time-based orientation evolution, reported in Fig. 4 where the convergence rates and shapes between P, PD and adaptive PD schemes are reported. The actuation effort acted by the azimuthal system is shown in Fig.5 where the "braking" activation function is also reported, showing that when the "braking" phase is active the azimuth start turning on the opposite side in order to slow down the steering (when reaching to the settling state).
The surge speed is also controlled with a standard PID scheme and the speed profile is reported in Fig. 6; the initial abrupt slow down is given by the immediate initial turning of the azimuth motors which deviates the thrust direction to the side of the platform, causing a surge force reduction and thus the speed is decreased. The speed tracking is immediately recovered to track, reach and maintain the reference value of 1.1 m/s.

The guidance system is then added and employed to follow a predefined path in the horizontal operating space. The proposed path-following methodology allows the tracking of generic continuous path. In this section two results are reported: a first one with the tracking of a rectilinear trajectory, while in the second a curved reference path is defined and fed to the guidance module. In the first scenario, following a rectilinear reference line shown in Fig. 7, the SWATH platform starts away from the line; tracking the desired speed profile it starts turning towards the line so to smoothly converge to the reference avoiding to overshoot and oscillate along the line.

In the second scenario, depicted in Fig. 8, the reference path is a curved trajectory; the vehicle is again initially positioned far from the desired path and, acquiring the final cruise speed, it starts its approach phase to the curve until the lateral distance is reduced to zero. In this case it is possible to notice a lateral deviation from the reference path during the motion; this fact to the limited turning curvature given by the platform dynamics, so that if the path is characterized by a local curvature with a higher value with respect to the maximum curvature that the vehicle can actually impose , the vehicle will not be able to properly steer on the reference and thus will be deviated outside the curve. The reference path will be tracked again once the local curvature will decrease.

5 Conclusions

The paper has reported the design and development of a reliable combined guidance & control scheme for the automatic navigation of an unmanned vessel characterized by azimuth-based thrust architecture. A custom

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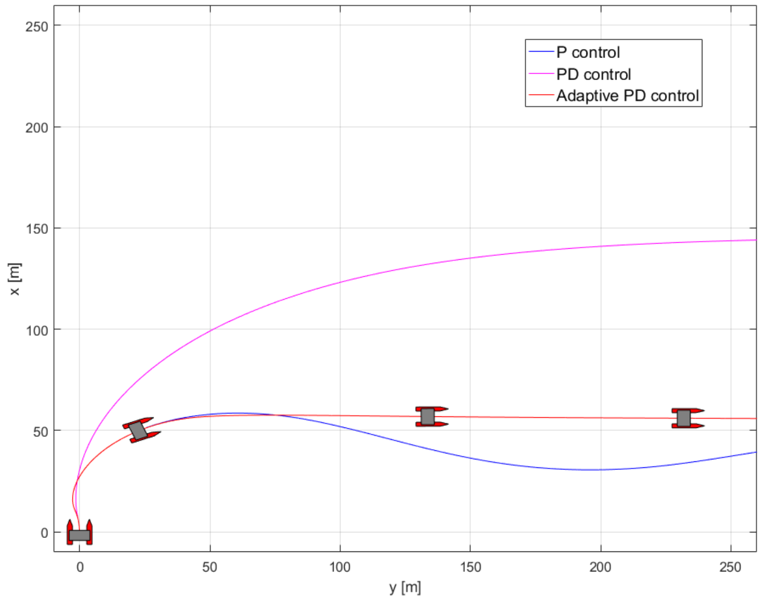

Figure 3: Motion generated by the thrust and course control system.

adaptive Proportional-Derivative control scheme has been implemented for the sake of the azimuth-based thrusters and it enhances the overall course tracking performance by allowing an increased convergence rate while at the same time avoiding overshoot and oscillation effects.
The guidance module is a Lyapunov based path-following scheme allowing the tracking of generic reference path which generates suitable course signals to be fed to the underlying control system, allowing a reliable geo-referenced navigation. Simulation results have shown the capabilities of the proposed approach with quantitative indication of the performance and limits. Further steps in the development will be application of the proposed scheme to a more refined dynamic model that will be obtained through at-field identification (validation and model-data comparison with respect to at-sea test data will be also carried out). In parallel, robustness of the guidance and control scheme with respect to environmental disturbances, uncertainties and measurement noise will be carried out to refine and tune up the overall scheme at best.

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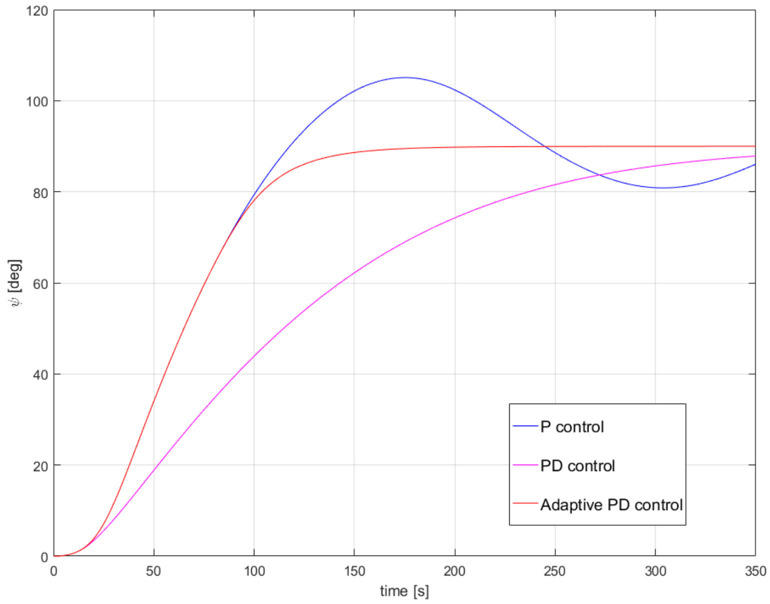

Figure 4: Orientation evolution under the control of the adaptive PD regulation scheme.

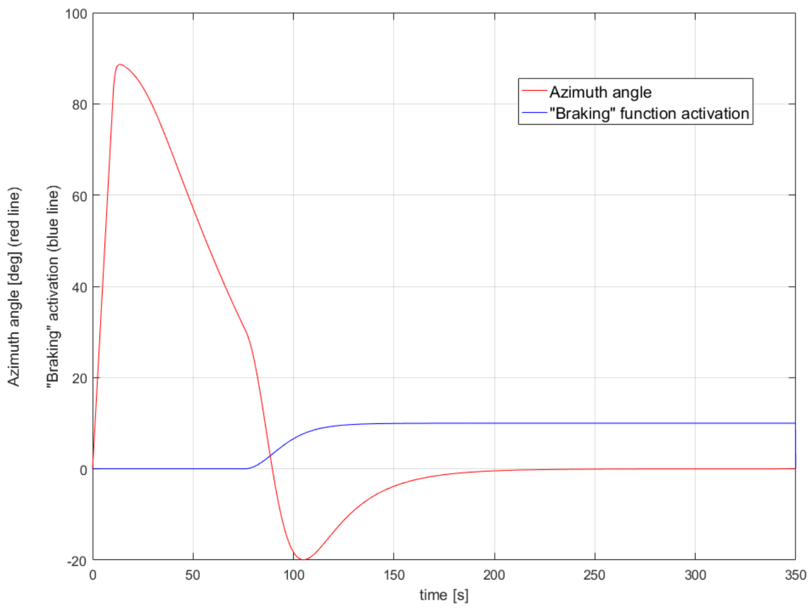

Figure 5: Motion of the azimuthal system commanded by the adaptive PD control.

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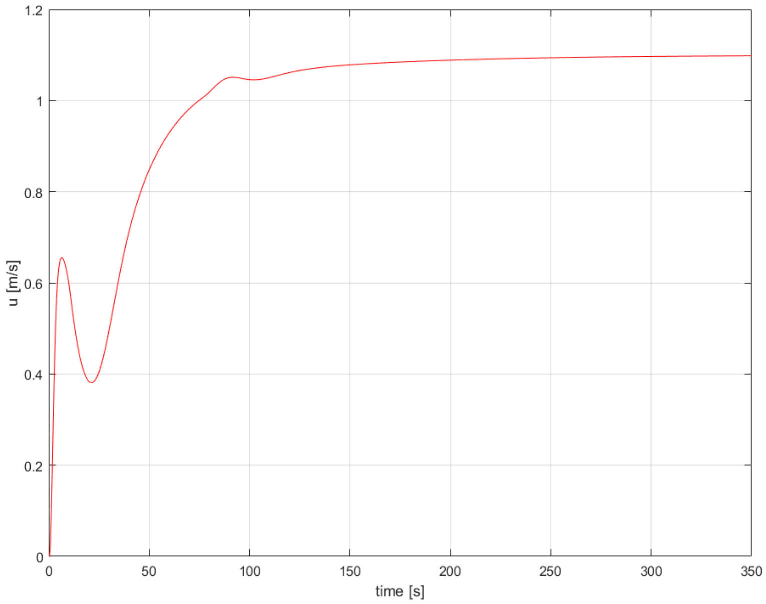

Figure 6: Controlled surge speed profile.

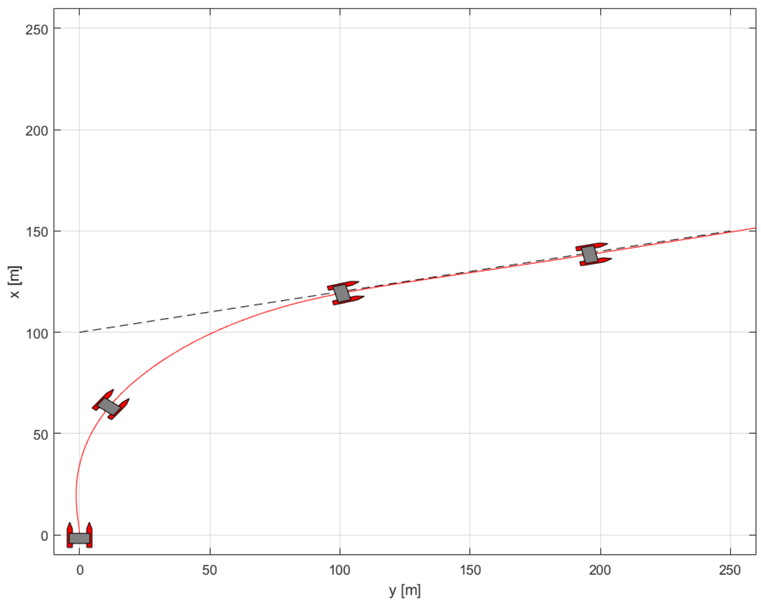

Figure 7: Path-following guidance along a rectilinear line.

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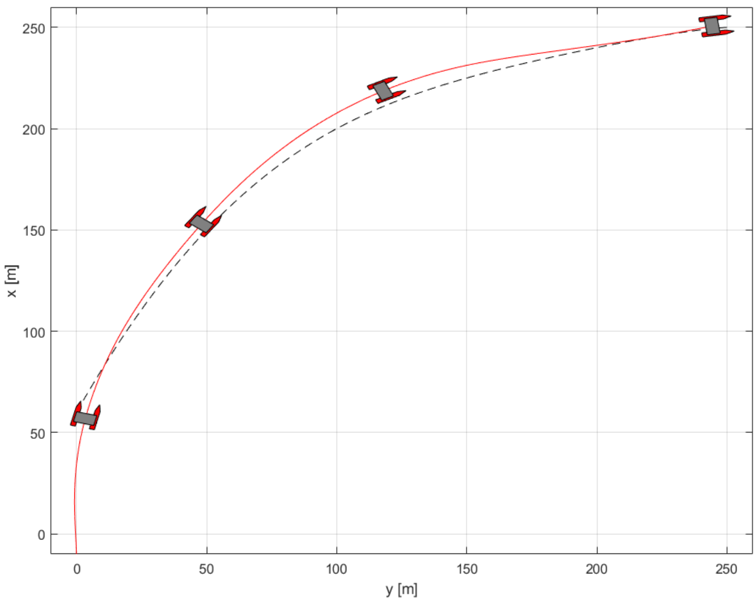

Figure 8: Path-following guidance along a curved trajectory.

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