

Article

Time Domain Design of a Marine Target Tracking System Accounting for Environmental Disturbances

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Abstract: Environmental disturbances represent significant challenges to the performance and accuracy of autonomous systems, especially in marine environments, where their impact varies based on disturbance severity and the employed guidance law. This paper comprehensively investigates a marine target tracking system using time-domain simulations incorporating realistic environmental disturbances. Three guidance laws and four key performance indicators are analysed to evaluate system performance under disturbed and ideal conditions. A robust and systematic evaluation pipeline is developed and applied to a case study featuring a scaled tugboat model. This approach provides a reliable method to assess tracking accuracy and robustness in adverse conditions. The results are selected from a wide range of possibilities to show the effect of the disturbances on the selected target tracking motion control scenario with two manoeuvres and two environmental conditions. The results are measured through the selected key performance indicators, and several phases are identified for each manoeuvre to extend the analysis not only to the global KPI values but also to the partial values of defined phases. They reveal the quantitative effects of environmental disturbances, exposing different system behaviours and trends. These findings demonstrate the effectiveness of the proposed pipeline in quantifying tracking system performance, delivering useful understandings of the system under environmental disturbances. The broader implications of this study are substantial, offering enhanced predictive accuracy for the performance of the analysed systems, particularly in the context of target tracking. Furthermore, introducing numerical key performance indicators facilitates a more rigorous comparison of different system characteristics, enabling informed decisions in designing and optimising autonomous operations in challenging environments.

Keywords: target tracking; environmental disturbances; marine autonomous surface ship



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1. Introduction

The demand for Maritime Autonomous Surface Ships (MASSs) is experiencing significant growth, driving increased research into their performance and design. These vessels are helpful in various sectors, including civil, military, and scientific research. Their diverse applications encompass inland and offshore surveys, bathymetric assessments, offshore wind farm support, and environmental monitoring. Additionally, MASSs are crucial in safety and rescue operations, where reconnaissance and surveillance are key tasks. Their ability to operate in large amounts of water, lakes, and water outlets, even during environmental disturbances, enhances their operational value.

MASSs can be designed to perform different tasks through their Guidance, Navigation, and Control (GNC) systems [1]. These tasks generally fall into two categories: those requiring control at high drift angles (managing three degrees of freedom) and those at low drift angles (managing two degrees of freedom). Tasks performed at high drift angles include station keeping and track keeping. Several works can be found in the literature with a variety of operations for tasks at high drift angles: the results of station-keeping are

investigated in [2]; an application of this kind of system for environmental monitoring is shown in [3]; a trajectory tracking system is proposed in [4]; an additional application of a trajectory tracking system with a focus on the docking strategy is shown in [5]; and in the end, a comprehensive review of dynamic position systems is carried out in [6]. Conversely, tasks at low drift angles include path following [7], which can be based on pre-defined or autonomously computed paths [8], formation control [9,10], and target tracking [11]. Several strategies can be found in the literature to perform the target tracking task, ranging from geometric approaches like the ones presented in [12,13] to those employing machine learning techniques as shown in [14,15]. For autonomous operation, these systems must integrate with navigation systems capable of tracking objects, as demonstrated in studies such as [16,17].

The impact of environmental disturbances on MASSs has been extensively studied, with parametric models used to quantify these effects based on the vessel's main dimensions. The effect of the wind includes both deterministic aspects, such as the mean wind speed, and random processes in time and space related to atmospheric turbulence. The aspects related to the mean wind speed are the most explored in the literature, and models accounting for this can be found in studies like the one proposed in [18–20]. Davenport, instead, explores the turbulences originating in the direction of the mean wind speed [21]. In addition, it is possible to find studies on the marine boundary layer at high wind speeds [22] and numerical implementations of three-dimensional wind fields [23] to analyse the dynamic response of structures. Likewise, the effects of currents can be modelled by considering the relative speed between the ship and the sea, as outlined in [24], or through parametric formulations like the one proposed in [25,26]. Design considerations may also factor in the interaction between the current generation and local wind influences, incorporating tidal components as described in Faltinsen's theory [27].

This study uses a time domain simulator based on the tugboat model Tito Neri to explore the marine target tracking guidance system presented in [28] under environmental disturbances. The target tracking scenario was initially inspired by missile guidance systems [29] and has been the focus of several studies in the literature, proposing both geometric and deterministic approaches as mentioned before. However, most studies in the literature are based on simulation tests without including environmental disturbance. Still, one study worth mentioning is the one in [30], where a real-world test of a target tracking system is reported regarding the resulting path and setpoints. Further, the effects of environmental disturbances are not explicit in the results. This paper aims to provide a pipeline to evaluate the influence of environmental disturbances on the performance of such a mode control scenario. The work carried out in this study builds upon the work presented in [28]. Here, a marine target tracking scenario that adopts the Line-Of-Sight, the Pure Pursuit, and the Constant Bearing guidance laws is presented together with the differences with respect to the ones in the literature, and the results stress the difference along with the three guidance laws using defined Key Performance Indicators (KPIs). The guidance laws presented in [28] have been slightly modified with respect to the literature to make them suitable for the parametric analysis carried out in the paper to assess the influence of the parameter present in the laws and to enable proper parameter set selection depending on the required performance. The tugboat object of the adopted time-domain simulator has an overall length of approximately one meter. Its behaviour is represented by a detailed non-linear model in the horizontal plane, including models accounting for wind and current effects. The wind and current forces are modelled using the parametric formulations for wind forces and moment of Blendermann [18], and the hull forces model of [24], both of which consider the relative motion components of the vessel. The structure includes the ship model, the target tracking guidance system, and a two-degrees-of-freedom control system. The control system comprises parallel PID controllers for heading and speed control, as employed in [7]. The performance of this system is evaluated under environmental disturbances using four KPIs based on integral metrics.

The paper proposes a methodology, in the author's best knowledge, lacking in the literature, to evaluate and test guidance logic and perform a quantitative performance evaluation under wind and current environmental disturbances. The proposed pipeline is applied to a case study, and a marine target tracking motion control scenario is selected to prove its validity. However, it can be generalised to other case studies and extended to generalised control scenarios by identifying additional evaluation parameters besides the ones already identified in the present study, which have led to the formulation of the four KPIs.

The paper is organised as follows. Section 2 introduces the simulation platform integrating environmental disturbances. Section 3 discusses the guidance laws. The control system structure is detailed in Section 4. The key performance indicators are presented in Section 5, and the results of the simulation campaign are discussed in Section 6. Conclusions are drawn in Section 7.

2. Simulation Platform

Simulation techniques let us know the behaviour of a vessel under different conditions, reducing the need for full-scale tests. They create a digital twin of the actual model through a set of differential or algebraic equations. The vessel object of this study is a tugboat named "Tito Neri", which has an overall length (L_{OA}) of 0.97 m and operates in three degrees of freedom. However, only horizontal plane motions, including surge, sway, and yaw, are considered. Three reference systems are introduced to define the ship model, as shown in Figure 1. The first frame is called $\{\underline{n}_i\}$ and is the north-east-down terrestrial reference system; its centre, Ω , is located in the mean surface at an appropriate position, and it is an inertial frame. The $\{\underline{b}_i\}$ frame instead is fixed with the tugboat and its centre $\Omega_I = x_I \underline{n}_1 + y_I \underline{n}_2$ is located in $(\frac{L_{PP}}{2}, 0, z_{WL})$, where L_{PP} is the length between perpendicular, and z_{WL} is the quota of the waterline above the keel line. The last frame $\{\underline{a}_i\}$ is fixed with the tugboat velocity; its origin is always Ω_I .

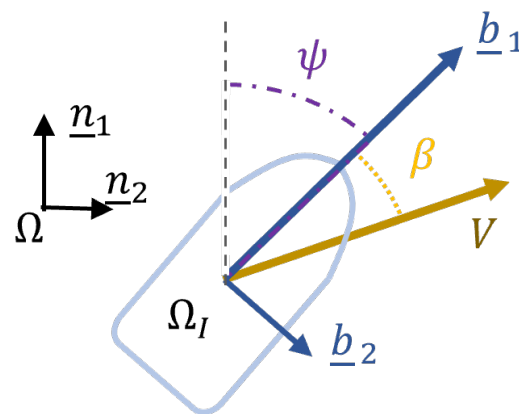


Figure 1. Reference frames.

The introduced reference system lies in the same plane, and the unit vectors are related by the Euler angle and the rotation matrices in (1).

$$\begin{aligned}\underline{n} &= R(\psi)\underline{b} \\ \underline{b} &= R(\beta)\underline{a}\end{aligned}\quad (1)$$

where ψ is the heading angle, β is the drift angle, and $R()$ is the rotation matrix.

2.1. Ship Model

The layout of the whole simulation platform is shown in Figure 2. The ship model in this section is shown in the area inside the dotted line. The guidance and control systems needed to compute the desired speed and heading and the relative actuator setpoint are linked

with the ship model. The guidance and control system will be explained in Section 3 and Section 4, respectively.

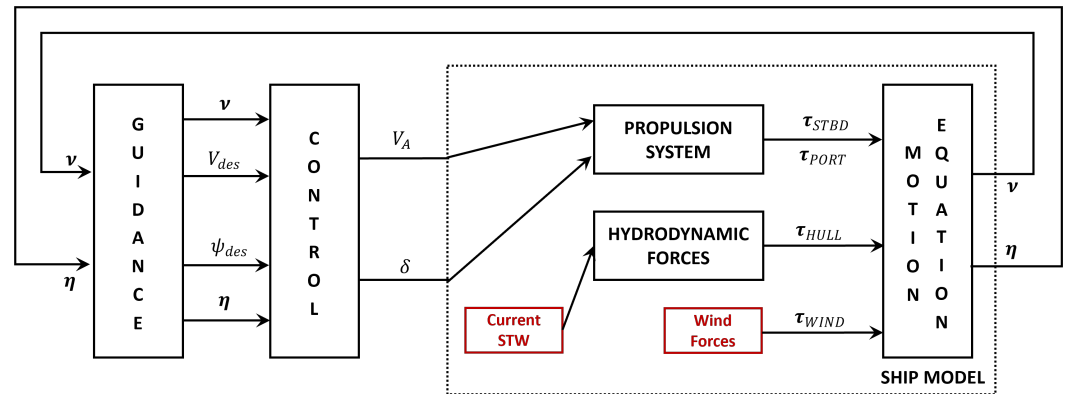


Figure 2. MASS simulation platform.

2.1.1. Propulsion System

The tugboat propulsion system is composed of two independent shaft lines. Each shaft line has DC motors that drive an azimuthal ducted propeller. Additionally, there is a separate DC motor-driven bow thruster, which enhances manoeuvrability at high drift angles, but that is not included in this scenario.

The output of each shaft line is computed by the “Propulsion system” blocks in Figure 2 and results in the forces and moment arrays $\tau_{port, stbd}$.

The differential equation in (2) describes the engine behaviour.

$$\frac{di}{dt} = \frac{R}{L}i - \frac{1}{L}K_e\omega + \frac{1}{L}V_a \quad (2)$$

where R represents the resistance, L is the inductance, i is the current, K_e is the electric engine constant, ω is the engine speed, and V_a is the applied voltage.

The shaft line dynamic can be expressed as in (3).

$$I_T \dot{n} = Q_{eng} - Q_{fric} - Q_0 \quad (3)$$

where Q_{eng} , Q_{fric} , and Q_0 are the engine, friction, and propeller torque, respectively, I_T denotes the total moment of inertia, and n represents the revolution regime of the shaft line.

The propeller force T and torque Q_0 are computed with a four-quadrant propeller model [31]. The model provides the non-dimensional thrust C_T and torque C_Q coefficients according to (4).

$$C_T = \frac{T}{\frac{1}{2}\rho\pi\frac{D^2}{4}V_r^2}, \quad C_Q = \frac{Q_0}{\frac{1}{2}\rho\pi\frac{D^3}{4}V_r^2} \quad (4)$$

where ρ represents water density, D is the propeller diameter, and V_r is the incoming velocity.

The azimuth angle δ is modelled by limiting the first derivative of the signal to take account of the maximum speed of the azimuth thruster. The adoption of this model is justified by the fast dynamics of the azimuth thruster of the real tug, which guarantees rotation at the desired speed since the maximum desired speed is lower than its limits.

The propeller force computed with the four-quadrant model is then rotated in the $\{b_i\}$ frame as shown in (5).

$$\tau_{port, stbd} = \begin{cases} X_p = T \cos \delta \\ Y_p = T \sin \delta \\ N_p = x_p Y_p - y_p X_p \end{cases} \quad (5)$$

where X_p , Y_p , and N_p are the forces and moment of the actuator in the $\{\underline{b}_i\}$ frame and x_p and y_p are the position of the actuator always in the $\{\underline{b}_i\}$ frame.

2.1.2. Hydrodynamic Force

Hull forces and moments are evaluated using the Oltmann and Sharma model [24]. The total hydrodynamic force is the sum of three main components: the ideal fluid force, which is evaluated by potential theory neglecting viscosity effects; the lift force, which compares the hull to a low aspect ratio wing; and the cross-flow drag, which represents the resistance due to viscous forces generated by a moving body in a real fluid. In addition, the hull drag is considered an independent term. The formulation of the hull forces and moments τ_{hull} is given in Equation (6).

$$\tau_{hull} = \begin{cases} X_{hull} = X_I + X_{HL} - R_T \\ Y_{hull} = Y_I + Y_{HL} + Y_{HC} \\ N_{hull} = N_I + N_{HL} + N_{HC} \end{cases} \quad (6)$$

where R_T represents the hull resistance, while subscripts I, HL, and HC refer to the Ideal Fluid Force, Lift Force, and Cross Flow Drag, respectively.

2.1.3. Motion Equation

The ship dynamics can be found using the equation of motion derived from the Newton–Euler formulation (7) and the kinetics equation in (8). From these equations and after an appropriate integration, it is possible to compute the pose $\eta = [x, y, \psi]$ in the $\{\underline{n}_i\}$ frame.

$$(M_{RB} + M_A)\dot{v} + C(v)v = \tau_{stbd} + \tau_{port} + \tau_{hull} \quad (7)$$

$$\dot{\eta} = R(\psi)v \quad (8)$$

where M_{RB} and M_A represent the inertial and added mass matrices, respectively; $v = [u, v, r]^T$ is the Coriolis matrix; v denotes the velocity in the $\{\underline{b}_i\}$ frame; and the external forces and moment are denoted by the array $\tau = [X, Y, N]^T$, with subscripts *stbd*, *port*, and *hull* referring to the starboard azimuthal thruster, port azimuthal thruster, and hull force, respectively.

2.2. Environmental Model

The purpose of the environmental model is to describe the effect of environmental disturbances quantitatively. In marine applications, the wind, wave, and current effects cannot be neglected, and the superposition principle is considered a good approximation, so these actions are summed in the force vector τ_{env} . This application will not consider wave action since the main dimension of the tugboat selected as the case study and since the selected environmental operation range is supposed to be without waves. This represents a limitation of this study, and an operational scenario that considers a proper wave action, scaled properly according to the main dimension of the tug, will be the subject of further investigation.

2.2.1. Wind

The wind movement is influenced by large-scale pressure variations. The result is an upper layer unaffected by friction with the earth and a lower layer affected by friction with the earth; however, it has a tapered speed profile. More details can be found in the studies by Davenport [21] and Faltinsen [20].

This study considers average wind speed, and gusts are added to the longitudinal component. The wind gust is modelled with the simplified model in [32] of Davenport's spectrum of horizontal gustiness.

The forces and moments due to the wind are computed by defining the wind with an incoming direction β_w (defined as clockwise positive with respect to $\underline{n}_1$) and a resultant velocity $V_w = u_w \underline{b}_1 + v_w \underline{b}_2$, as shown in Figure 3.

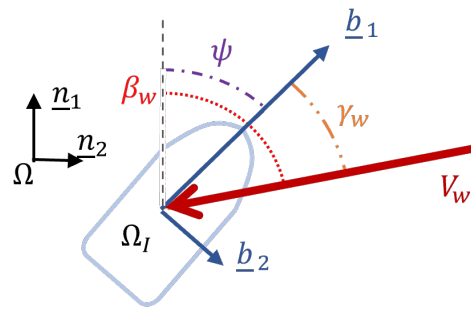


Figure 3. Wind reference frame.

The angle of attack of the wind γ_w is defined by (9) and the relative velocity $V_{rw} = u_{rw}\underline{b}_1 + v_{rw}\underline{b}_2$ according to (10). It is a composition of the ship speed $V = u\underline{b}_1 + v\underline{b}_2$ and the wind speed V_w . Finally, the relative angle of attack γ_{rw} is defined according to (11).

$$\gamma_w = \beta_w - \psi \quad (9)$$

$$V_{rw} = \sqrt{u_{rw}^2 + v_{rw}^2} \quad (10)$$

$$\gamma_{rw} = \text{atan2}(v_{rw}, u_{rw}) \quad (11)$$

where $u_{rw} = u_w + u$ and $v_{rw} = v_w + v$.

The Blendermann [18] model is adopted for computing the array of forces and moment τ_{wind} acting on the tugboat. This model provides a parametric formulation function of the relative wind speed V_{rw} and the relative angle of attack γ_{rw} . In this model, the angle of attack is defined as clockwise; hence, it is defined as $\varepsilon = 2\pi - \gamma_{rw}$. The resulting model is in (12).

$$\tau_{wind} = \begin{cases} X_{wind} = \frac{1}{2} \rho_a V_{rw}^2 C_X(\varepsilon) A_{Fw} \\ Y_{wind} = \frac{1}{2} \rho_a V_{rw}^2 C_Y(\varepsilon) A_{Lw} \\ N_{wind} = \frac{1}{2} \rho_a V_{rw}^2 C_N(\varepsilon) A_{Lw} L_{oa} \end{cases} \quad (12)$$

where ρ_a is the density of the air at 15° ; A_{Fw} and A_{Lw} are the frontal and lateral project areas exposed to wind; C_X , C_Y , C_N are wind resistance coefficients tabulated in [18] according to the tests on Helmholtz–Kirchhoff plates reported in [33,34] and depending on the vessel type.

2.2.2. Current

This study considers a constant current with irrotational motion and negligible acceleration. It is defined in terms of the incoming direction β_c (defined as positive clockwise with respect to the north) and the intensity V_c , as shown in Figure 4. The relative direction γ_c is defined according to (13). The relative speed V_{STW} is a function of the ship speed $\underline{V}$ and the real current $V_C = u_C\underline{b}_1 + v_C\underline{b}_2$, as shown in (14), and its angle γ_{stw} is defined according to (15).

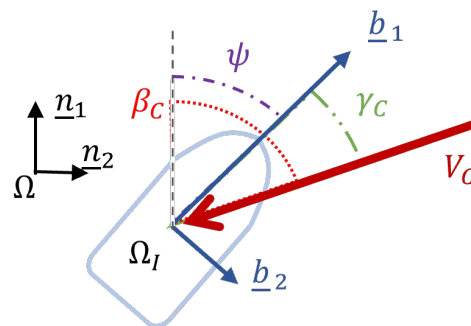


Figure 4. Current reference frame.

$$\gamma_c = \beta_c - \psi \quad (13)$$

$$V_{STW} = \sqrt{u_{stw}^2 + v_{stw}^2} \quad (14)$$

$$\gamma_{stw} = \text{atan2}(v_{stw}, u_{stw}) \quad (15)$$

where $u_{stw} = u + u_c$, and $v_{stw} = v + v_c$.

The effect of the current is introduced as a change in the hull forces τ_{hull} due to the speed through the water V_{STW} . The effect of the current is included in the differential equation describing the dynamics of the ship's motion.

3. Guidance

The guidance system consists of the motion control scenario known as target tracking. Its objective is to follow a moving object without prior knowledge of its future motion. To achieve the mission goal, the chasing ship, the interceptor, must have a maximum speed greater than the chased ship, the target. The scenario can be divided into two phases: the approach phase, where the interceptor needs to reach the target, and the following phase, where the interceptor has reached the target.

Three different guidance laws are adopted in this study: the Line-Of-Sight (LOS), the Pure Pursuit (PP), and the Constant Bearing (CB). A brief description is reported hereinafter, but further details about the laws can be found in [28], together with the analysis of the differences between these laws and the ones in the related literature.

3.1. Line-Of-Sight

The Line-Of-Sight (LOS) guidance minimises the difference between the real and desired trajectories. It is classified as a three-point guidance scheme since it involves a stationary reference point Ω_R in addition to both the interceptor Ω_I and the target Ω_T positions, as shown in Figure 5. In this logic, the interceptor is forced to move along the vector between the reference point and the target, named the LOS vector, to achieve the desired path.

Since the desired path depends instantaneously on the target kinematics, it is impossible to plan a series of static waypoints; hence, the reference point cannot be taken as the previous waypoints as in traditional Line-Of-Sight guidance [7]. The choice of the reference point is assessed as in [28]; briefly, it is selected as a previous point of the target path and its updated frequency increases together with the target trajectory curvature. The main idea behind this is that if the curvature of the target trajectory increases, it is necessary to introduce more reference points (however, to increase the updating frequency) to approximate the target trajectory with a polyline between the defined reference points. The updating frequency is one of the parameters investigated in [28] that affect the behaviour of the guidance law.

The desired heading ψ_{des} that allows the vessel to regain track is defined according to (16). The logic is based on nullifying the lateral error d_{err} between the desired path and the trajectory within a circle of radius $k L_{PP}$ (marked in purple in Figure 5).

$$\begin{aligned} \psi_{des} &= \alpha_k - \psi_{los} \\ \alpha_k &= \arctan \frac{y_T - y_R}{x_T - x_R} \\ \psi_{los} &= \arctan \frac{d_{err}}{\Delta_{LOS}} \\ d_{err} &= (\Omega_I - \Omega_R) e_2 \\ \Delta_{LOS} &= \begin{cases} \sqrt{(kL_{PP})^2 - d_{err}^2}, & kL_{PP} \geq d_{err} \\ (\Omega_T - \Omega_I) e_1, & kL_{PP} < d_{err} \end{cases} \end{aligned} \quad (16)$$

where ψ_{LOS} is the angle between $\underline{e}_1$ and the radius $k L_{PP}$, Δ_{LOS} is the projected distance of the target from the intercept point along $\underline{e}_1$, $\Omega_T = x_T \underline{n}_1 + y_T \underline{n}_2$ is the target position, and $\Omega_R = x_R \underline{n}_1 + y_R \underline{n}_2$ is the reference position.

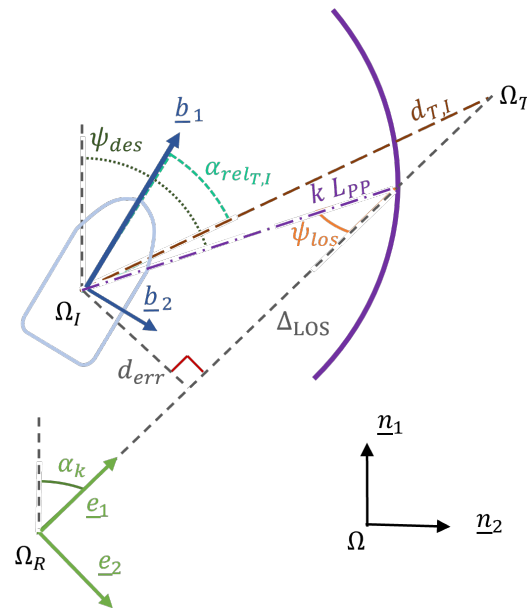


Figure 5. Geometrical sketch of the LOS guidance.

The desired velocity V_{des} depends on the distance $d_{T,I}$ from the target. The law is implemented to guarantee that the required velocity increases as the target moves away and tends to the target as the interceptor converges to the desired distance. The speed law is proposed in [28]. Hence, it is the ramp law of (17) and Figure 6. It is a function of the distance $d_{T,I}$, the defined slope p , and the selected distances $n L_{pp}$ and d^* .

$$V_{des} = \begin{cases} \frac{V_T}{2}, & d_{T,I} < -d^* \\ V_T \left(1 + \frac{d_{T,I}}{2d^*}\right), & -d^* \leq d_{T,I} \leq 0 \\ V_T, & 0 < d_{T,I} < nL_{PP} \\ V_T + p(d_{T,I} - nL_{PP}), & nL_{PP} \leq d_{T,I} \leq d^* \\ V_{max}, & d_{T,I} > d^* \end{cases} \quad (17)$$

$$d_{T,I} = (\Omega_T - \Omega_I) \underline{h}_1$$

$$\alpha_{rel_{T,I}} = \arctan \frac{y_T - y_I}{x_T - x_I} - \psi$$

where $V_{I_{\max}}$ is the interceptor maximum speed, $\alpha_{rel,T,I}$ is the relative bearing angle, V_T is the target speed, and V_{max} is the maximum speed admitted.

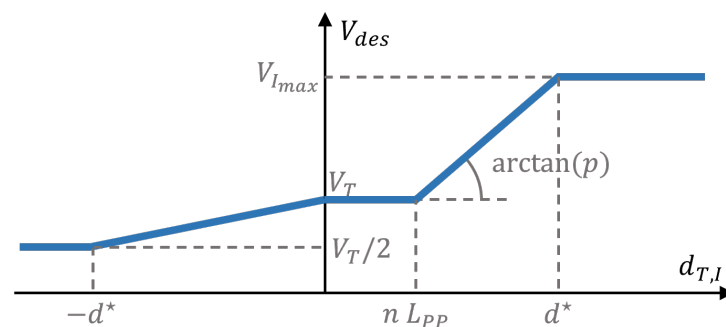


Figure 6. LOS speed law.

3.2. Pure Pursuit

The Pure Pursuit (PP) guidance points directly to the target, as shown in Figure 7, and aims to reach the target as soon as possible. This guidance is classified as a two-point guidance scheme; indeed, only the interceptor and the target are considered in the engagement geometry. It is based on the main idea of suiting the speed setpoint with respect to the distance between the objects. Indeed, the speed will increase as the distance between the ships increases according to the law in (18).

$$\begin{aligned} V_{des} &= K_{PP} \frac{d_{T,I}}{\sqrt{d_{T,I}^2 + \zeta_{PP}^2}} \\ d_{T,I} &= (\Omega_T - \Omega_I) h_1 \\ K_{PP} &= V_{I_{max}} \end{aligned} \quad (18)$$

where K_{PP} is a speed gain equal to the maximum allowable speed $V_{I_{max}}$, and ζ_{PP} is a parameter that affects the chasing phase and the distance at which it is possible to have a stable following phase.

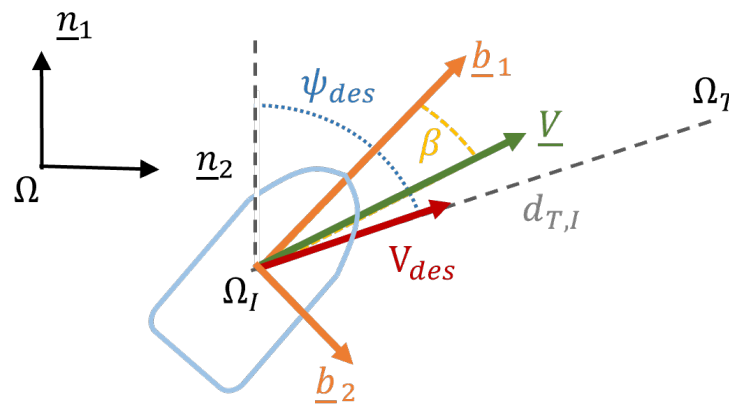


Figure 7. Geometrical sketch of the PP guidance.

According to [28], an adaptive relationship that allows tailoring the parameter ζ_{PP} to the desired distance d_D (user-defined) from the target is selected as shown in (19).

$$\zeta_{PP} = d_D \sqrt{\frac{K_{PP}^2}{V_T^2} - 1} \quad (19)$$

The heading law is taken from the geometrical sketch and shown in (20).

$$\psi_{des} = \arctan \frac{y_T - y_I}{x_T - x_I} \quad (20)$$

3.3. Constant Bearing

The Constant Bearing (CB) guidance law is based on parallel navigation since the interceptor must maintain a path parallel to the target path. The interceptor continuously adjusts its path as long as the distance between the target and the interceptor exceeds the desired one. A speed and heading law are implemented as functions of the desired distance e_{des} and s_{des} along the basis $\underline{f}$, defined fixed to the target speed. The geometrical sketch is shown in Figure 8.

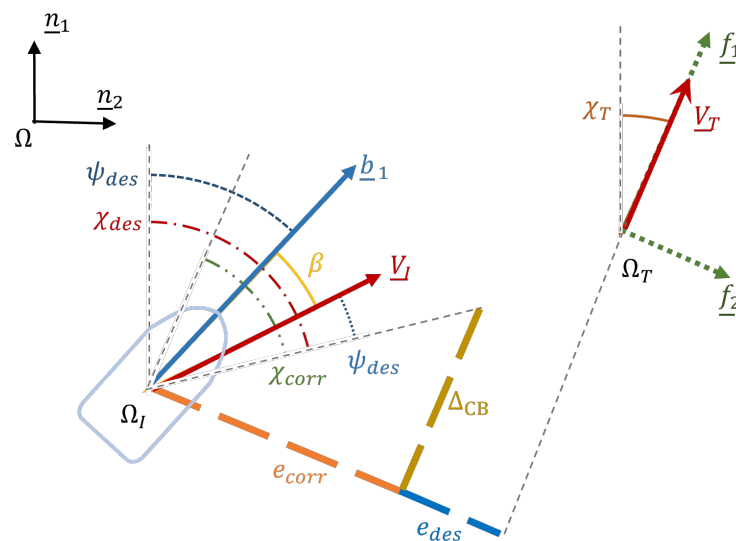


Figure 9. CB heading law.

4. Control

The control system plays a crucial role in determining the appropriate actions for the tug to achieve the control objective defined by the guidance system. As stated in the previous section, the guidance system provides two outputs to minimise the distance between the target and the interceptor: the desired heading angle (ψ) and the desired speed (V_{des}).

The control objective is satisfied by a smart pilot, an autopilot and a speed pilot working in parallel, as shown in the pipeline of Figure 10. The control inputs are the two desired values computed by the guidance (ψ and V_{des}) and the two feedback values coming from the ship model (ψ and V). The azimuth angle δ and the voltage setpoint V_A are the outputs.

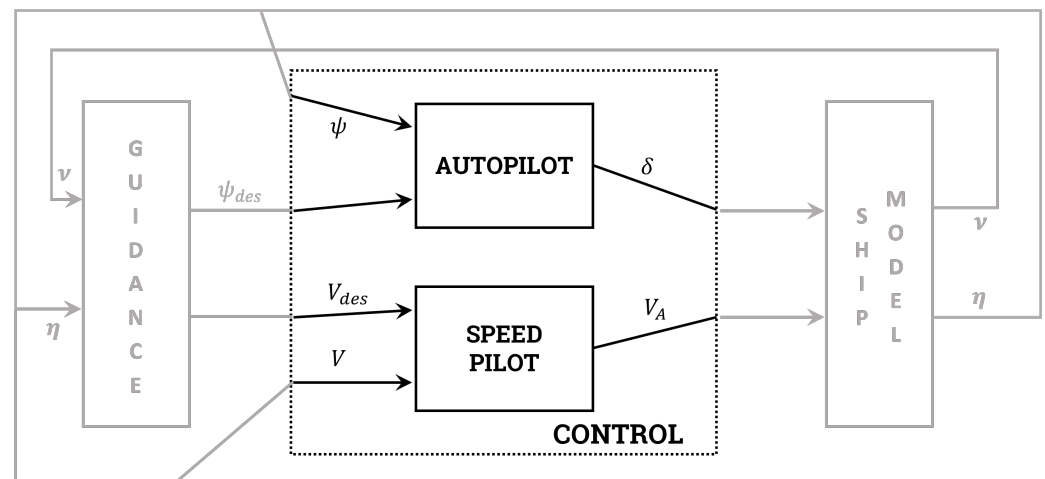


Figure 10. Smart pilot layout.

Both controllers are modelled as PID controllers and the output of these equations represents the values that minimise the error between the feedback and the desired value. The controller is modelled as in [7], and the coefficients are synthesised to guarantee the stability of the closed loop according to the Lyapunov theorem and to guarantee a limit on the overshoot of the controllable variables and a quick convergence on the desired values.

4.1. Speed Pilot

The first controller is a speed pilot, responsible for maintaining the desired ship speed and correcting deviations from that value. The instantaneous ship speed depends on the voltage setpoint computed by the PID of (23) as a function of the error $e_{SP} = V_{des} - V$ between the desired speed V_{des} and the feedback value V .

$$V_A = K_P e_{SP} + K_I \int_0^t e_{SP}(\tau) d\tau + K_D \dot{e}_{SP} \quad (23)$$

where K_P, K_I, K_D are the PID gains.

The step response is shown in Figure 11, where the desired speed signal is the step signal marked with the blue dotted line, and the feedback signal computed by the controller is marked in red. In this simulation, the tug is started with zero speed and is instantaneously asked to go at a speed of $0.8 \frac{m}{s}$. The system has a rise time of 3.82 s, quickly bringing it to the desired value. In the following instants and up to approximately 35 s, there is a constant response at a speed slightly higher than the desired value. It is caused by the saturation placed as a protection level on the voltage; indeed, waiting for the integral to discharge is necessary to eliminate the error and return to the desired value. Antiwindup techniques can be implemented to overcome this problem and further increase system performance.

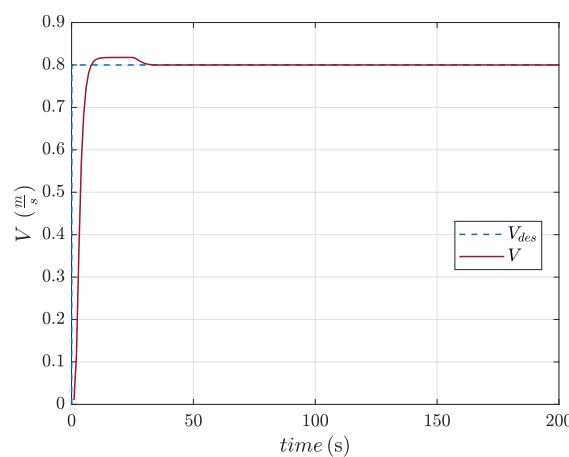


Figure 11. Speedpilot step response.

4.2. Autopilot

The second controller is an Autopilot, which is responsible for heading control. The instantaneous heading angle depends on the azimuth angle setpoint computed by the PID of (24) as a function of the error $e_{AP} = \psi_{des} - \psi$ between the desired heading ψ_{des} and the feedback value ψ .

$$\delta = K_P e_{AP} + K_I \int_0^t e_{AP}(\tau) d\tau + K_D \dot{e}_{AP} \quad (24)$$

where the parameters K_P, K_I, K_D are the controller gains.

The step response is shown in Figure 12, where the desired heading is the step signal marked with the blue dotted line, and the feedback value is marked in red. In this simulation, the tug is started with a heading of zero and is instantaneously asked to go to a heading of 30° . The system has a rise time of 4.67 s, quickly bringing it to the desired value. In the following instances, an overshoot of about 6° is present before settling on the desired value. Due to the poles of the ship system, additional conditions can be inserted into the synthesis of the control system to reduce the amount of this peak. The solution was a good compromise between response speed and overshoot angle.

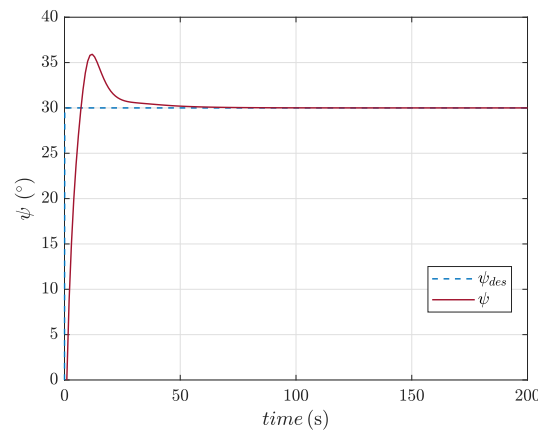


Figure 12. Autopilot step response.

5. Key Performance Indicators

The closed-loop performances are evaluated through some Key Performance Indicators (KPIs), which are expressed as integral metrics. The first formulation of integral metrics dates back to 1942 when the method of the derivative area to measure the control error was proposed for the first time [35] and from this, several metrics were proposed, leading to the well-known formulation defined in [36]. The metrics need to be selected according to the mission requirements. In this application, since the paper explores a target-tracking motion control scenario, the requirement is to follow the desired target in a given position and under different conditions defined by the law. Consequently, the metrics selected in this case will assess the error with respect to the desired trajectory in the target velocity basis $\underline{f}$ and the control action that was required to reach the desired position with the resulting error. Several KPIs can be formulated in accordance with the literature and the aim of the motion control scenario. In this paper, four KPIs have been identified to minimise their number while meeting the mission requirements for the target tracking scenario. Moreover, metrics providing only direct content, such as those related to energy consumption or mission completion time, were excluded from the analysis as the four chosen to provide this information intrinsically.

The first metrics is linked with the distance e , i.e., the projection of the vector $(\Omega_T - \Omega_I)$ onto the $\underline{f}_2$ basis. Evaluating e allows us to assess target trajectory overshoot since the $\underline{f}$ basis is aligned with the target velocity. The integral absolute error of the distance e time history IAE_e is selected in this case as a good indicator of all behaviours. Hence, the selected key performance indicator can be the one in (25).

$$e_{IAE} = \frac{||e| - |e_{des}||}{W_{e_{IAE}}} \quad (25)$$

$$IAE_e = \int_0^t e_{IAE} d\tau$$

where $W_{e_{IAE}}$ is the normalising weight.

In parallel, the second metric is linked with the distance s , which represents the projection of the vector $(\Omega_T - \Omega_I)$ along the $\underline{f}_1$ basis. The integral absolute error of the distance s time history IAE_s influences manoeuvring stability during the following phase. The KPI can be formulated as in (26).

$$s_{IAE} = \frac{||s| - |s_{des}||}{W_{s_{IAE}}} \quad (26)$$

$$IAE_s = \int_0^t s_{IAE} d\tau$$

where $W_{s_{IAE}}$ is the normalising weight.

The third and fourth metrics want to evaluate the control action during the entire simulation. The third one is linked with the derivate of the control action $\dot{\delta}$. The normalised control action $\dot{\delta}_{IAC}$ can be integrated, leading to the integral absolute control KPIs, as shown in $IAC_{\dot{\delta}}$ of (27). This metric is linked with the movement of the actuators.

$$\begin{aligned}\dot{\delta}_{IAC} &= \frac{|\dot{\delta}|}{W_{\dot{\delta}_{IAC}}} \\ IAC_{\dot{\delta}} &= \int_0^t \dot{\delta}_{IAC} d\tau\end{aligned}\quad (27)$$

where $W_{\dot{\delta}_{IAC}}$ is the maximum derivate of the azimuth angle.

The fourth metric takes into account the derivate of the control action $\dot{V}_A$. The normalised derivative of the voltage setpoint $\dot{V}_{AIAC}$ is integrated, leading to the integral absolute control KPIs, as shown in $IAC_{\dot{V}_A}$ of (28). This metric can be linked to energy consumption.

$$\begin{aligned}\dot{V}_{AIAC} &= \frac{|\dot{V}_A|}{W_{\dot{V}_{AIAC}}} \\ IAC_{\dot{V}_A} &= \int_0^t \dot{V}_{AIAC} d\tau\end{aligned}\quad (28)$$

where $W_{\dot{V}_{AIAC}}$ is the maximum derivative of the azimuth angle.

6. Results

The defined pipeline is tested through the execution of two manoeuvres and evaluated through the four KPIs described in Section 5 to quantify the effects of the environmental disturbances on the proposed pipeline.

The adopted manoeuvres are:

- Manoeuvre A: provides a path with two consecutive direction changes between 60° , similar to a zigzag that ends in 560 s, as shown in Figure 13a. The manoeuvre is divided into five phases to assess the KPIs in the different sections. The following phases are identified:
 - Phase 1: from the beginning of the simulation until 60 s. It corresponds to the initial phase of the simulation in which the target moves along a straight path, and the interceptors, which started with a 60 s delay with respect to the target, must reach the target.
 - Phase 2: from instant 60 s to instant 130 s. It corresponds to the first change of direction and is a transient phase.
 - Phase 3: from instant 130 s to instant 310 s. It corresponds to the second straight line in which the three interceptors return to the desired following position after the change of direction and continue their pursuit phase.
 - Phase 4: from instant 310 s to instant 380 s. It corresponds to the second change of direction and is also a transitional phase in which the interceptors must reach the target again at the desired position.
 - Phase 5: from instant 380 s to the end of the simulation. It corresponds to the third and last straight line with the last pursuit phase.
- Manoeuvre B: presents several variations of the heading angle, similar to a double execution of a Williamson turn manoeuvre that ends in 900 s, as shown in Figure 13b. The manoeuvre is divided into seven phases in order to assess the KPIs in the different sections. The following phases are identified:
 - Phase 1: from the beginning of the simulation until 150 s. The manoeuvre starts in position (0,0) and has a first straight phase with a heading of 45° . It is the initial phase of the manoeuvre, where the interceptors must reach the target and compensate for the initial delay.

- Phase 2: from instant 150 s to instant 300 s. This phase is characterised by a change of direction of approximately 225° .
- Phase 3: from instant 300 s to instant 445 s. This phase is characterised by the second straight section, where the interceptors return to the desired position in the following phase.
- Phase 4: from instant 445 s to instant 520 s. A change of direction characterises this phase.
- Phase 5: from instant 520 s to instant 650 s. This phase is characterised by a third straight section in which the interceptors return to the desired position in the following phase.
- Phase 6: from instant 650 s to instant 800 s. This phase is characterised by a change of direction of approximately 270° .
- Phase 7: from instant 800 s to the end of the simulation. Finally, the simulation ends with the last phase involving a straight line.

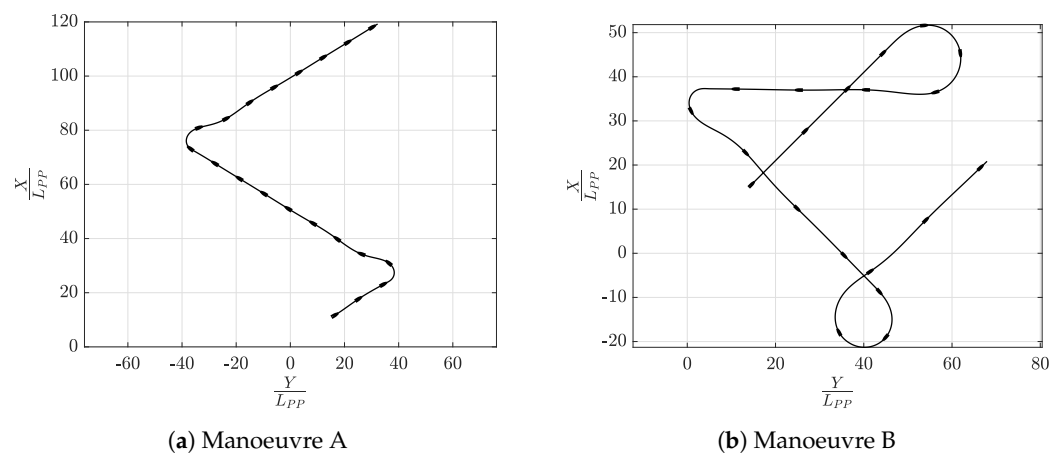


Figure 13. Testing manoeuvres.

The interceptor vessel follows the target in a target tracking scenario using the three guidance laws discussed in Section 3. During the simulation, the vessels are subjected to the action of the environmental wind and current disturbances investigated in Section 2.2. The wind disturbance comes from 60° with respect to the north at a speed of 0.4 m/s in manoeuvre A and 0.2 m/s in manoeuvre B. For both manoeuvres, the current is a disturbance also coming from 60° with respect to the north, with a speed equal to 10% of the speed held by the target. The delay at the initial time step of the interceptor with respect to the target is equal to 60 s in both manoeuvres.

In all the figures, the target time histories are marked in black, while the LOS, PP, and CB are marked in red, blue, and green, respectively.

The trajectories regarding manoeuvre A are reported in Figure 14 for all guidance logics. In the first part of the manoeuvre, the two vessels are oriented 60° with respect to the north; hence, they see the environmental disturbances coming from the bow. In the second part of the manoeuvre, the disturbances act transversely with respect to the tug, and the effect produced is a slight drift of the interceptor. In the final part, the disturbances act again from the bow. From the time histories, it is possible to see how the three guidance logics manage to follow the target: the CB sets itself in a parallel trajectory, the PP points directly to the target, while the LOS tends to return to the desired trajectory within a certain distance (this is evident after the second turn). The effect of the disturbances is noticeable in the second part.

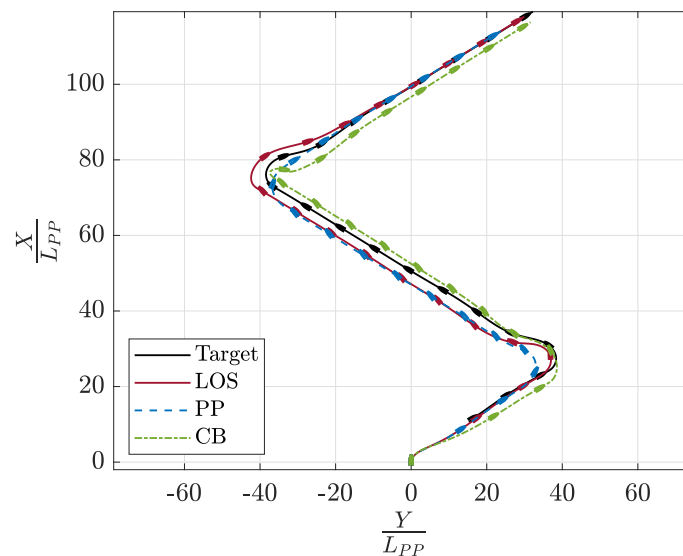


Figure 14. Ship trajectory in presence of environmental disturbances—Manoeuvre A.

Figure 15 shows the trajectories regarding manoeuvre B. Here, the vessels see the environmental disturbances from all the coming directions while executing the different parts of the manoeuvre. The most significant difficulties for all three guidance laws are found in executing the second knot (the one with the centre in $(40, -15)$) due to the magnitude of the disturbances and the relative proximity between the vessels. However, all three logics are able to follow the target in the desired way.

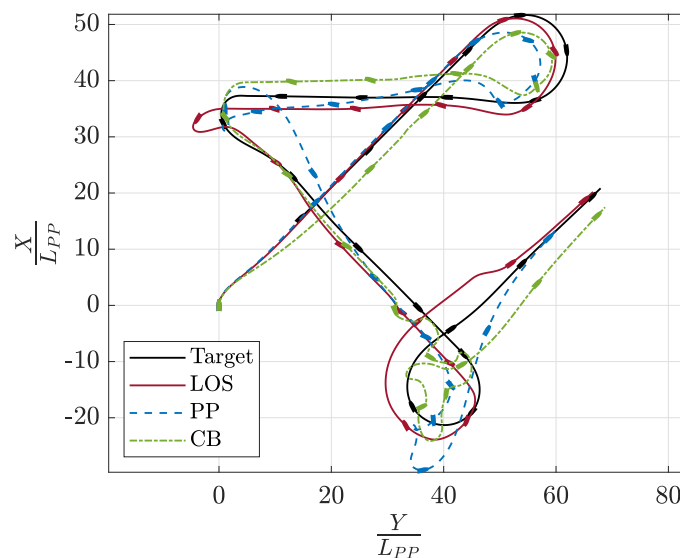


Figure 15. Ship trajectory in presence of environmental disturbances—Manoeuvre B.

The KPI's time histories are reported in the absence (dashed line) and presence (continuous line) of the environmental disturbances with the same colour legend adopted before.

The time histories of the IAE_s and IAE_e indices for manoeuvre A are reported in Figure 16a,b, while the ones regarding manoeuvre B are reported in Figure 17a,b. In all plots, vertical dashed black lines are added to better distinguish the manoeuvre phases described at the beginning of this section. The KPI values at the last time step are reported in Table 1 for an overall comparison, while the partial KPI values of each phase are shown in Tables 2 and 3 for manoeuvres A and B, respectively. From the results, it is possible to make some general comments. First of all, from the analysis of the values of IAE_e and IAE_s

of the same guidance law with and without disturbances for the overall simulations (value in Table 1) and for each phase (partial value of each phase in Tables 2 and 3), it is possible to see that introducing environmental disturbances in the simulation leads to higher KPIs due to higher errors. The only exception is the results concerning manoeuvre A with the Constant Bearing law. Indeed, in this case, in the last change of direction, in the simulation conducted without disturbances, there is a significant deviation due to the relative position between the two vessels that leads to a lateral error and to a larger IAE_e respect to the one with environmental disturbances. It is highlighted from the time history in Figure 16b, where it is possible to see that the green dotted line increases more in the last phase with respect to the continuous green line and from the difference of the values of IAE_e of the phases 4 and 5 of Table 2 of the Constant Bearing law with and without disturbances. From the time histories shown in the figures, it is possible to draw another general comment; however, after each change of direction, the KPI values tend to stabilise since the approach phase ends and the following phase in the desired position starts. When the IAE_e and IAE_s do not reach a constant value after the initial transient phase, the approach phase does not start since the desired position has not been reached, and the reason must be investigated. An example can be found in phase 3 of manoeuvre A of the Pure Pursuit guidance law, where the external disturbances from the side of the ship introduce a lateral error that the logic can not stabilize. In particular, there is an increase in the 443% and 76% in the final value of IAE_e for the LOS and PP logics with the disturbances due to phase 3 of the manoeuvre when it drifts. Another general comment that can be drawn is related to the initial phase (i.e., phase 1) of both manoeuvres and the IAE_s index. Here, the IAE_s index sees a similar trend but is in extremely transient phases in which the driving laws implement setpoints to compensate for the initial delay. Moreover, it is possible to see that the phases characterised by direction changes (phases 2 and 4 for manoeuvre A and phases 2, 4, and 6 for manoeuvre B) register the most significant partial values without disturbances, as expected.

The time histories of the IAC_δ and $IAC_{\dot{V}_A}$ for manoeuvre A are reported in Figure 16c,d, while those regarding manoeuvre B are reported in Figure 17c,d. The KPI values in the last time step are reported in columns three and four of Table 1, while the partial KPI values of each phase are shown in Tables 2 and 3 for manoeuvres A and B, respectively. Also, in this case, it is possible to draw some general comments. Analysing the values of $IAC_{\dot{V}_A}$, it is possible to see that their values are comparable with and without disturbances for the first three phases of both manoeuvres. This means that disturbances do not lead to higher power consumption even if the performances are not comparable, following what is seen from the values of IAE_s and IAE_e . Starting from phase 4 of both manoeuvres, the values have few peaks in the approach phases (phases 2 and 4 for manoeuvre A and phases 2, 4, and 6 for manoeuvre B), which means that in these phases, higher power consumption is needed to try to reduce the distance errors. The effect instead of disturbances on the δ control variable has a different impact on manoeuvres A and B. Indeed, in manoeuvre A, it can be seen that the three guidance laws produce higher values of the index in approach phases 2 and 4 without disturbances, as shown in the partial KPI values of Table 2. It is due to the relative position between the vessel and the disturbances since in phases 1 and 5, they are coming from the bow and do not modify the bow of the interceptor, while in phase 3, the disturbances affect the vessel from the side and there is no correction of the lateral error. The only exception is phase 4 of the Constant Bearing guidance law, where the azimuthal thruster deletes the distance error in the manoeuvres with a disturbance that is instead present in the one without disturbances, as said before. In manoeuvre B, it is possible to see instead that greater azimuthal movements follow the target in the presence of disturbances, as expected. It is also shown by the partial results in Table 3, where the manoeuvres with disturbances have higher partials. The reason can be found behind the kind of manoeuvres that will cross more relative directions of the environmental disturbances.

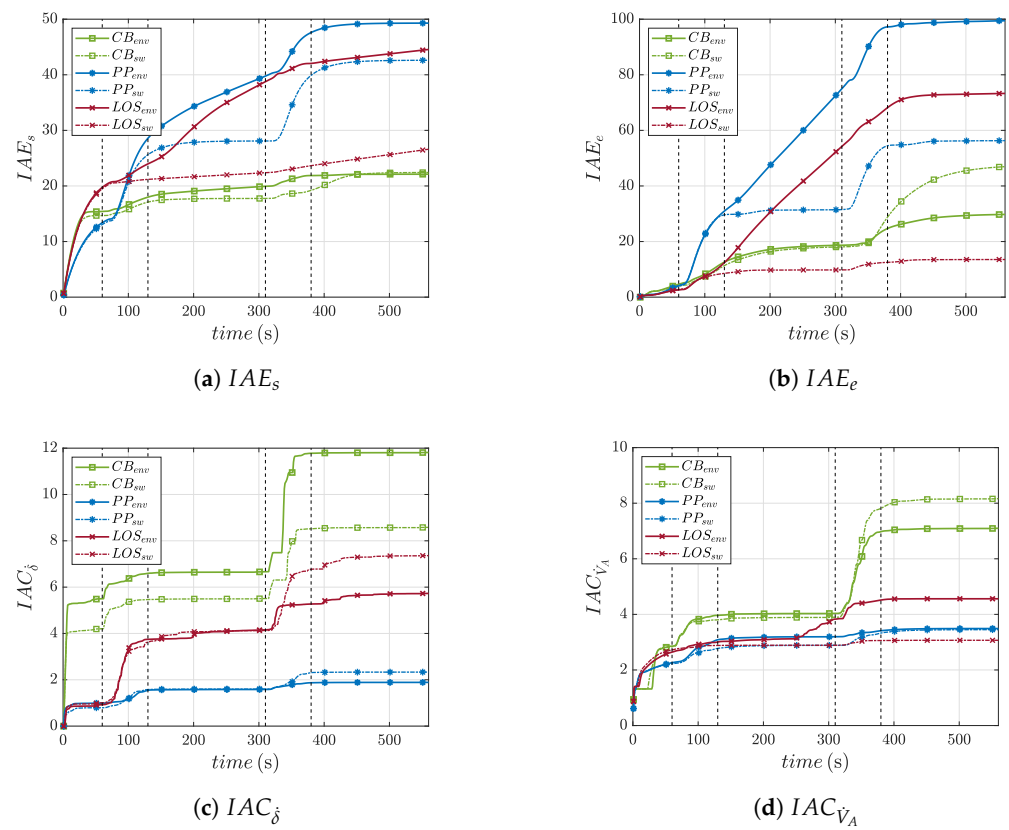


Figure 16. KPI performance—Manoeuvre A.

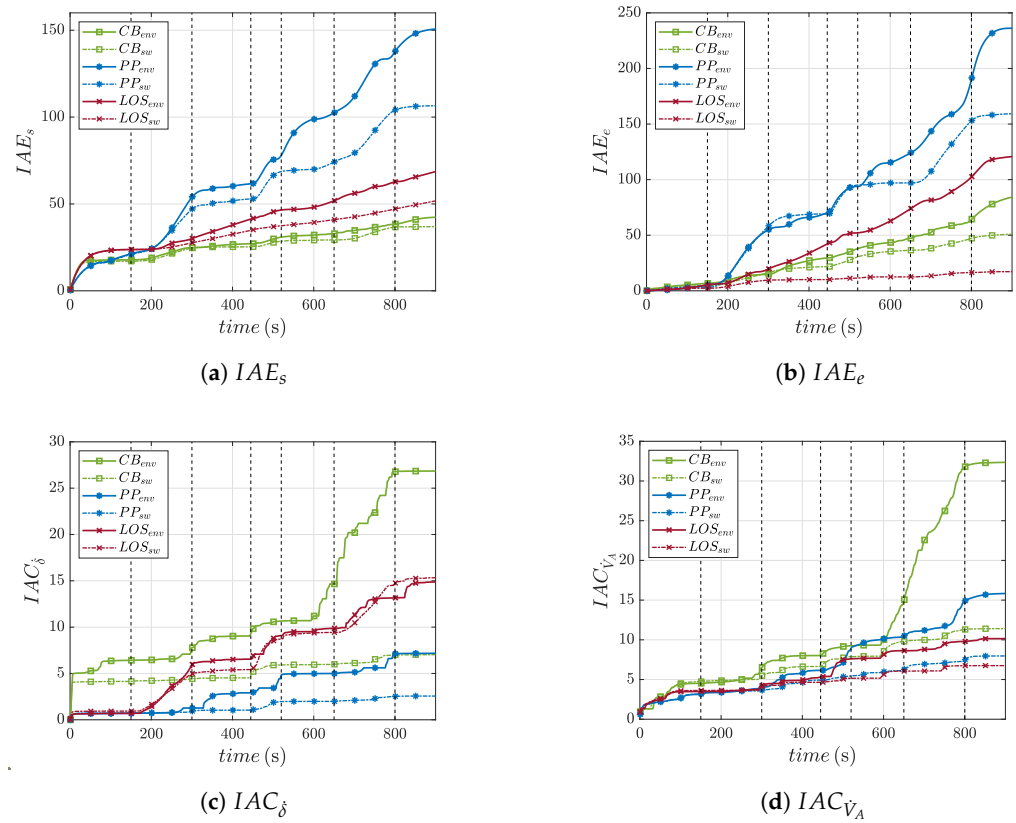


Figure 17. KPI performance—Manoeuvre B.

Table 1. KPI values at the last time step.

Path	Test	$IAC_{\dot{V}_A}$	$IAC_{\dot{\delta}}$	IAE_e	IAE_s
A-sw	LOS	3.1	7.4	13.5	26.6
A-env	LOS	4.6	5.7	73.3	44.6
A-sw	PP	3.4	2.3	56.3	42.6
A-env	PP	3.5	1.9	99.4	49.3
A-sw	CB	8.2	8.6	47	22.4
A-env	CB	7.1	11.8	29.8	22.1
B-sw	LOS	6.8	15.3	17.2	51.8
B-env	LOS	10.1	14.9	120.8	68.6
B-sw	PP	7.9	2.6	159.2	106.5
B-env	PP	15.8	7.2	236.2	150.7
B-sw	CB	11.4	7	50.9	36.9
B-env	CB	32.3	26.9	84.2	42.3

Table 2. Partial KPI values of Manoeuvre A.

Path	Test	Phase	$IAC_{\dot{V}_A}$	$IAC_{\dot{\delta}}$	IAE_e	IAE_s
A-sw	LOS	1	1.9	1	2.6	18.8
		2	0.16	2.6	5.8	1.7
		3	0.008	0.5	1.2	1.2
		4	0.17	2.6	2.7	1.3
		5	0.008	0.6	1	2.9
A-env	LOS	1	1.8	0.9	2.4	19
		2	0.36	2.8	9.8	4.2
		3	0.82	0.41	42	14.8
		4	0.68	1.1	14	3.3
		5	0.046	0.46	5	2.5
A-sw	PP	1	1.6	0.8	4.1	12.7
		2	0.55	0.8	25	12.6
		3	0.11	0.02	1.9	2.5
		4	0.44	0.7	23	12
		5	0.13	0.02	1.9	2.7
A-env	PP	1	1.66	0.98	3.8	13
		2	0.83	0.56	27	15
		3	0.11	0.03	44	11
		4	0.22	0.3	22	7.8
		5	0.08	0.017	2.2	1.7
A-sw	CB	1	1.9	4.2	3.9	14
		2	0.97	1.2	7.4	2.4
		3	0.095	0.044	6.7	0.66
		4	3.9	3	11	1.5
		5	0.35	0.064	18	3.2
A-env	CB	1	1.9	5.5	4.6	15
		2	1.1	1.1	7.9	2.6
		3	0.07	0.07	6	1.9
		4	2.9	5.1	6	1.9
		5	0.12	0.035	5	0.25

Table 3. Partial KPI values of Manoeuvre B.

Path	Test	Phase	$IAC_{\dot{V}_A}$	$IAC_{\dot{\delta}}$	IAE_e	IAE_s
A-sw	LOS	1	2.7	0.8	2.3	23
		2	0.45	3.9	7.3	3.9
		3	0.57	0.52	0.53	7.2
		4	0.5	3.3	1.4	2.6
		5	0.9	0.71	1.1	3.5
		6	0.7	5.3	3.9	6.1
		7	0.01	0.65	0.76	4.7
A-env	LOS	1	2.6	0.7	5.1	23
		2	0.74	5.2	14	6.3
		3	1.1	0.71	23	11
		4	2.3	2.5	9.9	5.2
		5	1	0.79	22	5.3
		6	1.2	3.3	29	11
		7	0.35	1.7	18	6
A-sw	PP	1	2.6	0.72	3.2	20
		2	0.44	0.2	55	26
		3	1.3	0.12	11	6
		4	0.53	0.92	26	16
		5	0.75	0.017	1.9	5.4
		6	1.2	0.54	56	29
		7	0.56	0.02	6.3	2.5
A-env	PP	1	2.5	0.69	5.2	21
		2	0.8	0.57	50	33
		3	2.2	1.6	15	7.8
		4	2.8	1.9	24	16
		5	1.5	0.15	30	24
		6	4.4	2.1	66	35
		7	0.97	0.057	46	13
A-sw	CB	1	3.8	4.1	4.6	16
		2	0.73	0.27	12	7.6
		3	1.2	0.33	5.4	0.68
		4	1.2	1.2	8.8	3.25
		5	1.9	0.066	5.9	0.74
		6	1.5	1	11	7.4
		7	0.11	0.032	3.8	0.25
A-env	CB	1	3.6	6.4	6.6	17
		2	1.9	1.3	8.3	6.9
		3	1.6	1.5	14	2.3
		4	1.2	1.4	8.3	3.8
		5	5.6	4	9.3	1.9
		6	17	12	17	5.5
		7	0.6	0.067	20	3.9

All of these considerations can help identify the best steering law for each type of manoeuvre. Indeed, from the results displayed, it is possible to conclude that for manoeuvres with smooth changes of direction and with disturbances acting on the side of the vessel, the Constant Bearing law is the only one that corrects the drift, allowing the tracking phase to be carried out in the desired position and not with a lateral error leading to large values of IAE_e . The opposite effect, however, is a more significant movement of the actuators, which is minimised in the Pure Pursuit law, which pays more significant errors. Similar considerations can also be made when there are significant changes of direction greater than 200° , as in the case of manoeuvre B. In this case, it is possible to see how these significant heading variations affect the tracking performance and how environmental disturbances worsen its performance.

7. Conclusions

This paper presents a pipeline to evaluate the influence of the disturbances on marine motion control scenarios and the results of a marine target tracking system that accounts for environmental disturbances. The pipeline uses a time domain simulation and KPIs to evaluate the performance. The detailed numerical ship and environmental model, the smart pilot, the three guidance laws, and the four KPIs adopted are presented with the simulation results and analysis.

The pipeline identified to assess the system performance with and without environmental disturbances proved to be effective and successful. The time domain simulation approach demonstrated the remarkable accuracy of the results and the level of detail and differentiation between the different guidance laws, while the selected metrics proved to be able to be used to assess the different reactions of the guidance logic to the introduction of disturbances at the level of both accuracy and implementation. The results, therefore, showed that the pipeline could be applied to provide information on the possible limits for the mission accomplishment in terms of both manoeuvring and maximum environmental disturbances with the different guidance laws. Another possible application is to select the appropriate guidance law based on the expected performance in terms of accuracy, consumption, and actuator movement to meet the operational limits imposed by the mission.

The application of the proposed pipeline is limited to the tugboat case study, and although the tests are carried out for different environmental conditions, the results are reported for one environmental condition selected as an example. Furthermore, given the size and operating conditions of the selected case study, disturbances derived from the waves are not considered. Therefore, further studies will aim to generalise the pipeline and the influence of the disturbances in each guidance law: other vessels with different propulsion plants can be considered, and the results found can be reported in such a way as to show different environmental disturbance conditions. Moreover, the presented guidance laws will be properly tailored to environmental factors, e.g., the wave effect, to better identify the potential scalability of the study. Investigation of the results found with several environmental disturbances can be investigated more and can be represented in a statistical way that can lead to the definition of a statistical index that will define the operability of the case study in the selected motion control scenario. Further future developments may include the wave effect on ships in case studies that allow this or a properly scaled introduction of additional KPIs combining precision and actuator motion, and the tests of the proposed pipeline with the real hardware infrastructure.

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