Two-Dimensional Vessel–Current Interaction Model for Inland Waterways Assessment

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Abstract: This study presents a computational tool for the analysis of commercial navigation capacity of rivers by a fast-time two-dimensional vessel–current interaction model. Different scenarios of rivers and vessels can be simulated, and the model can be used during early-stage design and overall management of inland fairways. The mathematical description relies on the 6DOF equations, where Eulerian flows and a Lagrangian ship-tracking approach is used, coupling river features and the main characteristics of ships. For each time step, the resultant linear and angular momenta were calculated through analytical equations to measure the ship movement and other relevant parameters such as velocity and drift angle. An autopilot system was also developed to reproduce the necessary maneuvers during navigation. A German section of the Rhine River was used for verification. The model reproduced the main movements of vessels in restricted regions; therefore, one can estimate the set of parameters and necessary adaptations in rivers and ships that optimize safe commercial navigation for waterways projects. **DOI: 10.1061/(ASCE)WW.1943-5460.0000494.**

Introduction

The study of inland waterways is a multidisciplinary task related to areas of geotechnics, hydrology, hydraulic and hydrodynamic modeling, and general issues of planning and logistics. The management becomes even more complex when adjustments to increase safety are necessary,which are usually due to natural conditions of watercourses and require detailed surveys, analysis, and modeling. Furthermore, engineering measures to improve navigability are planned to optimize the hydraulic system and to preserve its natural morphology (i.e., mitigation of environmental impacts).

Navigation safety is one of the key issues for any channel design (Briggs et al. 2003). This can only be guaranteed by detailed studies of the river system (Horritt and Bates 2002), ship motion (Varyani 2006; Lataire et al. 2012; von Graefe et al. 2015), and traffic management (Ince and Topuz 2004). Nowadays attention should also be given to the multiple uses of water resources, such as urban supply and hydroelectric generation, reinforcing the need for studies to seek optimized use of rivers.

Even if a model produces a good representation of the river system, the simple understanding of the channel geometry and flow are not sufficient to ensure safe and optimal navigation. Skaggs and Bastian (1986) published a review of studies using hydrodynamic modeling to assess cargo transport in rivers and maritime fairways. Most articles emphasized the relevance of the interaction analysis between vessels and the velocity field for waterways projects (i.e., the modeling of vessel movement).

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Navigation in restricted waterways (e.g., rivers) has several aspects that are different from navigation in the marine environment (Constantine 1960). First, inland waterways are usually limited in depth and width. Therefore, the river bathymetry and sediment transport patterns must be periodically studied (Assine 2005; Henning et al. 2007; Rijn 2007). The curvature radius analysis is also essential to ensure navigability conditions. Graewe (1971) described the relation of this parameter with ships' dimensions, velocities, and maneuverability capacities. In order to improve navigation, rivers receive artificial interventions such as groins and locks. These hydraulic constructions impact the flow and must also be analyzed.

Currently, several studies can be used as references to assist in evaluating waterways projects as proposed by Blaauw and Verhey (1983), McCartney (1986), Magirl and Olsen (2009), and the PIANC guidelines (e.g., PIANC 1995, 2011), where the latter are the most often used standards.

Frequently, river systems have specific and complex features and the guidelines may not be sufficient to optimize these waterways projects. As an example, Brazilian authorities are using PIANC regulatory standards (PIANC 1995) to design and operate inland waterways in the country. The 1995 standard currently in use is considered rather restrictive (ITTI 2014) and not ideal for Brazilian rivers. Even though several river sections have not been evaluated as safe by the used guideline, commercial navigation is occurring, especially in the Paraguay River. Specific studies for navigation assessment are required, particularly studies using small-scale physical models and numerical computer models.

Physical models are usually small-scale experiments in which a large range of parameters is analyzed during the ship movement. The experimental configuration is carefully set using dimensional analysis, for example, Froude and Reynolds numbers. The results of these tests are important to evaluate effects such as hydrodynamic forces on ships (Kume et al. 2006), effects of currents (Hüsig et al. 2000; Kolarov 2006), and overall ship stability (Fitriadhy et al. 2013). However, for large river sections this approach may be considered expensive and complex; thus a great variation of parameters and scenarios may be unfeasible.

Numerical models are an advanced approach for ship navigation studies. They have advantages of easy variation and the analysis of

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several parameters. However, the validity of these models is limited by the data availability and by the mathematical approach they are based on (Linke et al. 2015).

According to Benedict et al. (2017), numerical motion simulators can be used as research tools for waterway investigations and design, studies to evaluate the maneuvering capabilities of new ships, and for overall decision making. Navigation simulators are models that couple environmental characteristics (e.g., velocity field), physical aspects of the region (e.g., depth, width, curvature radius), and vessel features (e.g., dimension, power, maneuverability) to evaluate the ship motion within a defined fairway. These models can run real-time or fast-time simulations.

Usually, real-time simulators have a control room (ship bridge) with all the equipment and controls necessary to enhance tests (Harlacher et al. 2015) and are used for specific situations and regions, for example, in crew training for difficult operations. Fast-time simulators are most often applied to evaluate and optimize general parameters related to navigation (Linke et al. 2015; Benedict et al. 2017). The main objective of these programs is the prediction of the maneuverability of a ship—based on limited input and without the use of any a priori information of the ship's maneuvering derivatives—by simulating a specified set of standard maneuverer within a short time frame (Toxopeus, unpublished data, 2006).

There is a knowledge gap in the highly complex and expensive assessment of inland waterways projects, especially during early stages. A fast-time model is proposed that can, by using relatively few parameters of rivers and vessels, evaluate the capacity of inland waterways to provide commercial navigation. Thus, given the main characteristics of rivers, flow, and vessels, the two-dimensional (2D) model calculates the vessel–current interaction and provides information relevant to the design and management of waterways. The river velocity field is analyzed using a Eulerian approach, whereas for the ship-tracking a Lagrangian frame of reference is applied. The model is open source and has been built so that new features (e.g., forces and coefficients) can be easily added or modified.

Vessel–Current Interaction Model

Research and modeling of vessel motion and maneuverability in complex flows is challenging because it requires, on one hand, a good knowledge of the fluid motions to compute the forces on the ship and, on the other hand, a good knowledge of ship maneuvers under certain conditions and as a consequence of changes in the fluid flow (changing velocity field) or changing boundary conditions (e.g., river banks, shallow regions, other ships). Features of the former can be simulated quite satisfactorily using sophisticated hydrodynamic models. Simulation of the latter, however, depends on numerous additional factors that do not in general follow a clear deterministic behavior. Compared with other previous studies on ship maneuverability, this study is focused on a simplified approach, aiming for analysis of larger regions, with fast response. The following simplifications were considered:

- Large river situation: Using only horizontal flow motions, thus a 2D approach. Effects of vertical velocities or effects due to ship motions in the vertical were considered negligible. Consequently, wave effects from narrow channels were neglected too.
- Integral force considerations: The fast-response method requires a coarse grid, which is not sufficient to compute pressure or velocity changes for the ship–flow interaction and thus does not allow for the computation of the resistance forces in full detail. The forces were computed as integral forces using the mean velocity field at the ship position and the ship geometry and angle.
- One-way coupling: The effects of the ship motion on the fluid flow were neglected. Thus, the fluid flow was computed in advance and without considering the ship. The velocity data was then used as boundary conditions for the ship movement calculations.
- Steady flow: The ambient velocity field was assumed to be steady; thus no flow changes were implemented during the simulations.
- The ship maneuvers are represented only by changes of azimuth thruster force and direction. Their variation is computed by a so-called autopilot system.

The method proposed by this research is designed to be easily implemented and used to analyze any force affecting the vessel motion, making it possible to define the path of the ship for any set of parameters and to estimate those that optimize navigation. The most important feature is that the model evaluates the river navigability condition for any vessel, river flow, and fairway project. The physical basis of this model relies on the conservation of linear and angular momenta, on the six-degrees-of-freedom (6DOF) equations, and on hydrodynamic forces.

Mathematical Description of Motion

The fast-time vessel–current interaction model relies on the discretization of ships as rigid bodies moving within a river velocity field, where the ship propulsion and the hydrodynamic forces interacting with the vessel are responsible for the overall movement.

The mathematical description of the ship motion, that is, translation and rotation, is based on the 6DOF equations, proposed by Kirchhoff (2009). These equations consist of a general system describing a 3D rigid body motion in a fixed reference system.

The 6DOF equations can be obtained by the derivation of the kinetic energy equation in relation to velocities in the linear and angular momentum equations, resulting in three expressions of forces, one equation for each direction, and three for torques, one equation for each axis of rotation. For sake of conciseness, this mathematical procedure is not presented in this paper and was detailed by Kornev (2013).

Following the discretization of the 6DOF equations, several inertia-related parameters are necessary for the earth-fixed reference system. However, when a ship-fixed reference system is adopted, the inertia moments, products of inertia, and static moments can be disregarded. Another hypothesis can be used to simplify the ship motion equations: (I) the ship mass distribution is symmetrical and (II) the off-diagonal elements of the inertia matrix and static moments are zero. This hypothesis can be satisfied by a special choice of the location of origin and direction of the coordinate system axes.

Using the previous hypothesis, the 6DOF equations arise for the forces

$$F_x = m\left(\frac{dv_x}{dt} + v_z\omega_y - v_y\omega_z\right),$$
$$F_y = m\left(\frac{dv_y}{dt} + v_x\omega_z - v_z\omega_x\right),$$
$$F_z = m\left(\frac{dv_z}{dt} + v_y\omega_x - v_x\omega_y\right). \quad (1)$$

and torques,

$$\tau_x = I_{xx}\frac{d\omega_x}{dt} + \omega_y\omega_z(I_{zz} - I_{yy}),$$

$$\tau_y = I_{yy}\frac{d\omega_y}{dt} + \omega_x\omega_z(I_{xx} - I_{zz}),$$

$$\tau_z = I_{zz}\frac{d\omega_z}{dt} + \omega_x\omega_y(I_{yy} - I_{xx}), \quad (2)$$

where x, y, and z = longitudinal, transversal, and vertical components; F = forces; m = ship mass; τ = torques; I = inertia moment; v = linear velocity; and ω = angular velocity.

The movements in the model are 2D, in the transversal and longitudinal directions. The vertical component is not considered, given the premise that in wide and shallow rivers the effect of waves can be generally disregarded, especially for vessels that carry heavy loads and present low-speed navigation. In addition, among major drag components of such ships, the free-surface wave component is very small due to the low speed, where the skin frictional drag component occupies approximately 80% of the total drag (Kodama et al. 2000). Heave, pitch, and roll motions do not affect the ship maneuverability, which relies only on the ship yaw. Thus, for the rigid body dynamics in a plane (x–y)

$$v_z = \omega_y = \omega_x = 0. \quad (3)$$

Finally, the resultant force and torque for a 2D rigid body is given by

$$F_x = m\left(\frac{dv_x}{dt} - v_y\omega_z\right),$$

$$F_y = m\left(\frac{dv_y}{dt} + v_x\omega_z\right),$$

$$\tau_z = I_{zz}\frac{d\omega_z}{dt}. \quad (4)$$

F_x and F_y = sum of all forces (i.e., resultant force, in x and y direction, respectively); and τ_z = resultant torque applied in the ship center of mass and around the vertical (z) axis in the x–y plane.

For each time step, the model presents a resultant force and torque. These results are then used to calculate the linear and angular acceleration, velocity, and motion of the ship by classical kinematic equations. The main forces that accelerate the rigid body are described in the following section.

Hydrodynamic Forces

The forces that vary the rigid body acceleration within the velocity field are mostly due to the surface–flow interaction (hull forces) but also due to propulsion forces (ship thrusters and steering devices). The difficulties in determining these forces arise in the calculation of pressure and shear stress components because these terms are related to the shape of the body of the ship. Currently, the state of art for these analyses is related to the use of computational fluid dynamics (CFD), which is usually applied in the optimization process of immersed rigid structures such as ships (el Moctar et al. 2012). These algorithms divide the body surface into a high spatial resolution computational mesh, calculating the pressure variation in each node to obtain resultant forces and pressures.

Despite the good representation provided by CFD software, the analysis of the pressure distribution in rigid bodies requires a great amount of data, which is not always available during the initial stages of a waterways projects assessment. It is important to emphasize that for this research the perspective is not of the optimization of the structure of ships or its maneuverability, but in obtaining the average navigation displacement. For these cases, another possible solution is using analytical semiempirical equations, which although simpler can provide relevant information to the modeling process.

The analytical determination of the hydrodynamic forces is complex and mostly has not yet been solved for general cases; thus experiments and simplifications are required. For this study, the authors sought consolidated analytical expressions in the literature to represent the forces and their coefficients. Initially, the algorithm considers the form and friction drag, added mass, and propulsion forces as being the most relevant in describing the ship motion.

Regarding the hull forces, several works have presented advanced approaches for the determination of linear and nonlinear components (e.g., Hooft 1994; Hooft and Quadvlieg 1996; Toxopeus, unpublished data, 2006). These studies have proved effective in modeling hydrodynamic forces; however, their processes require the previous calibration of ship parameters. This paper presents a simpler proposal for the modeling of these forces so that the model can incorporate the initial conditions of waterway projects, that is, the sparse data.

The skin–friction drag coefficient can be estimated by the analysis of the flow speed distribution in a field near the surface of a rigid body, an approach known as the boundary layer theory (Prandtl 1905) and well described by Schlichting (1966). The hypothesis of the vessel–river interaction simplified as a parallel flow over a plate is an approximation used in many studies of ship movement (Milgram 1998; Kodama et al. 2000; Usta and Korkut 2013) in which the skin–friction coefficient depends on the Reynolds number near the plate–flow region. For this study, the skin–friction drag coefficient for ships was obtained by the equations presented in the International Towing Tank Conference (ITTC) guidelines (Acevedo and Mazarredo 1957).

The form drag coefficient can be determined by scale-model experiments. Several authors have researched and published experimental results for different bodies morphologies and Reynolds numbers. For the model presented here, one can set specific pressure drag coefficients for the published data of different types of vessels. According to ITTC guidelines (Acevedo and Mazarredo 1957), the form factor, that is, the form drag coefficient, can also be estimated by a relation between the ship total resistance and the frictional drag coefficient. Min and Kang (2010) presented a detailed review of the form factor of different ship designs; thus whenever data of the total drag is not available, one can estimate the form drag coefficient published for a similar vessel or one can vary this parameter during calibration.

The added mass is the inertia added to a system due to an accelerating body within a flow, which shifts some volume of the surrounding fluid as it moves through it. Added mass or virtual mass is a common issue given that immersed bodies and the surrounding fluid cannot occupy the same physical space simultaneously. A detailed overall description and necessary hypothesis have been described by several authors (Brennen 1982; Kornev 2013; Sen and Vinh 2016). Analytical solutions for the added mass are possible for bodies with simple geometries. Given the consideration of a 2D rigid body to represent a ship, the research presented here used the solution for an elliptical cylinder to calculate the added mass coefficients. See Kornev (2013) for further details.

Propulsion forces are due to the vessel thruster, that is, engine force. This force is responsible for accelerating and maneuvering the ship. For each instant of time, the azimuthal thruster can apply a force ranging from 0% to 100% of its maximum capacity in any direction, generating torque and causing angular acceleration in the rigid body. The magnitude of the force depends on the vessel's power and has been previously defined for each simulation and varies according to autopilot instructions.

Necessary Input Data

The model input data are related to general characteristics of the simulation, flow, and physical aspects of rivers and vessels. Fig. 1 presents a diagram summarizing these parameters, which can be obtained by databases or specific field surveys. For each simulation, it is necessary to configure the model parameters. This can be easily set by the use of a graphical user interface (GUI) framework developed within the main program (Fig. 13). The data matrix is then stored for simulation, analysis, and post-processing.

The data resolution may vary according to the availability of information to be simulated. As presented in Fig. 2, each position operates as a vector, and the necessary data is stored for the modeling process. Furthermore, the geospatial information, latitude, and longitude of the river and flow data, can be easily loaded in Esri Shapefiles format.

The river data are the bathymetry, navigation path, the margin coordinates, and the position and size of obstacles to navigation (e.g., bridges and groins).

The navigation paths are designated lines within the river to be followed by the ships. These lines are composed of points with the recommended position and angle for upstream and downstream navigation. Usually, the vessels a position maintain close to its right margin of the river (starboard). However, this may vary according to river conditions in specific stretches, such as when there are restrictions due to the flow or the bathymetry. In these regions, signaling is used so that the vessels stay in the center of the navigation channel or even change to a position relative to the other margin.

The flow data are composed of the velocity field for the desired condition, for example, for low, mean, and high water levels. This information can be obtained by using 1- and 2D models of rivers or by direct measurements in the field. The result is usually high-density georeferenced points distributed within the river for a steady-state simulation. These points present information such as magnitude and direction of the flow along the river. The flow varies in space; however, the authors considered the hypothesis that no major temporal variation occurs during the navigation of the ships. The model is thus the steady-state result of a simulation with

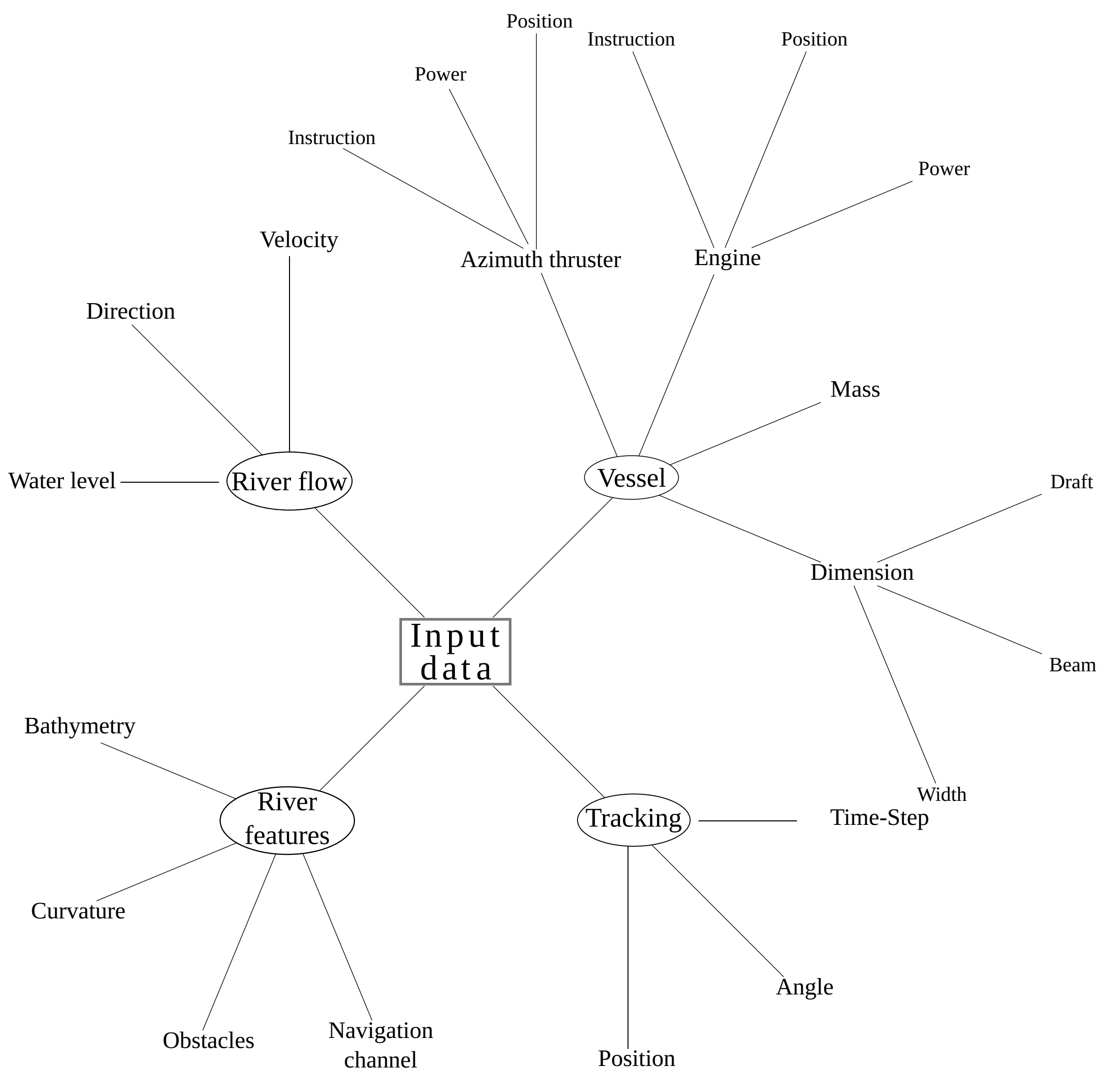


Fig. 1. Model main input data parameters.

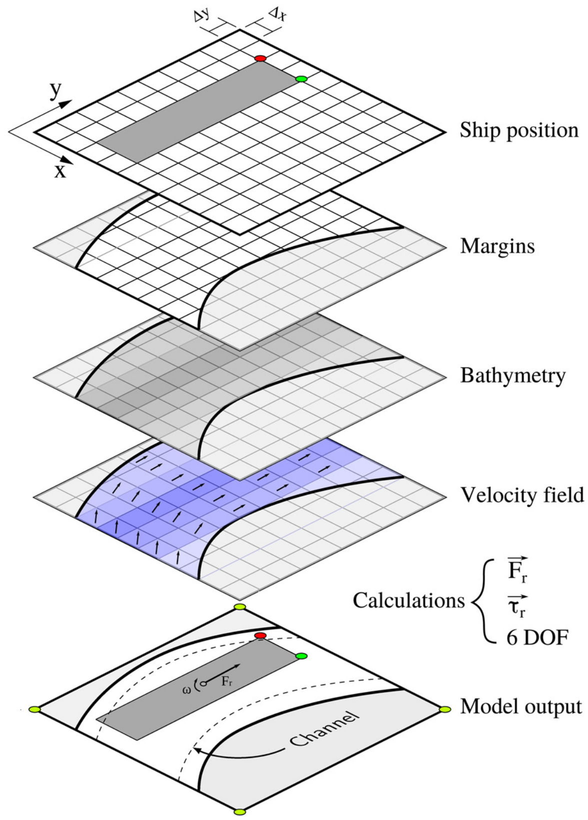


Fig. 2. Model spatial data input.

constant boundary conditions (invariant in time). In addition, the velocity field is assumed to be not affected by the movement of ships.

Regarding vessel characteristics, the model loads the convoy (pusher and barges) draft, length, and width. The total weight, center of mass, thrust power, and the azimuth thruster characteristics are also required. By default, the hydrodynamic forces' coefficients are determined using the previously described methods; however, specific values may also be set.

Model Algorithm

The computer algorithm was written using Matlab and Python (version 2.7) programming languages. The concepts of rigid body dynamics are applied in the discretization of the vessel in a finite number of sections, that is, ship-discrete points. The number of sections can be predetermined and each discrete point represents a proportional and constant amount of the total mass and surface area of the ship. During navigation, the points of the vessel present distinct physical responses to the forces and torques. The sum of these responses gives the resultant force and torque vectors for the entire ship. Both the engine and azimuth thruster are placed on the vessel stern, in the transverse axis of symmetry.

The ship velocity can be set by three main parameters: the engine power, the resistance force during navigation (ship–flow interaction), and the force applied by the ship. The engine power is obtained by a database, whereas the resistance force must be calculated for each time step. Using the engine power as a constraint, one can vary the force applied by the ship to increase and decrease the vessel speed, whereas the velocity variation can be controlled by the autopilot system.

Initially, the software loads the described input data. As shown in Fig. 2, the vessel occupies a certain area and each position on the computational grid has an array of data for calculations. In addition to the engine thrust, the forces affecting the vessel are due to its interaction with the river velocity field. As detailed in Fig. 3, for each time interval the algorithm identifies data points within the vessel area (rectangles). The magnitude and direction average of the flow is calculated and used in the estimation of the hydrodynamic forces.

Then, for a determined interval (Δt) the forces (e.g., drag, thrust) acting on each section are calculated. It is possible to determine for each Δt the resulting force ($\vec{F}$), linear acceleration ($\vec{a}$), torque ($\vec{\tau}$), angular velocity ($\vec{\omega}$) and acceleration ($\vec{\alpha}$), overall velocity ($\vec{V}$), and position ($\vec{s}$) of the vessel. The calculations occur until a simulation constraint is reached. These constraints may be the simulation time or impediments to the vessel movement, such as contact with obstacles, the river bed or channel banks, and the occurrence of excessive velocity. A summary of the model algorithm is presented in Fig. 4.

Autopilot System

The development of an autopilot system was necessary to reproduce the ship maneuvers in rivers and, given the natural difficulty in emulating human behavior under changing ambient conditions, presented a great challenge. Autopilots are widely used in air and train traffic. Intensive research is currently underway for autopilot systems for cars and trucks, as well as for ships. Compared with planes and trains, the car and ship systems need to respond to many more external factors and make faster decisions under several options. Furthermore, the high inertia of a ship's movement increases the system decision and complexity of the maneuvers.

The additional challenge for a ship's autopilot system is the fact that even though the navigation channels are fixed, the flow velocities and water level are continuously varying. Furthermore, technical literature published on this subject is scarce. The authors developed an autopilot system that evaluates a small number of parameters and navigation rules, responding (maneuvers) at each simulation time step. Currently, the input data are georeferenced points and angles with respect to the navigation channel, which is the path to be followed by ships. Thus, the model user needs to specify a navigation channel or a track beforehand. However, as a starting point could be the thalweg too. The autopilot is programmed such that the ship tries to navigate as close as possible to these points and also tries to maintain the correct angles. In future versions of the model, the user will be able to specify any desired parameter for each river section (e.g., angular velocity) and the autopilot will vary the ship parameters to seek the reference value. In the model GUI, the user can select to use the autopilot or not. If the autopilot is not being used, the ship navigates forward and movements occur only due to the ship–flow interaction. When the autopilot is selected, its script is activated and it works as described herein.

For each simulation time step, the system detects which points are close to the ship and which of these points can be used as a reference for the maneuver action. Possible maneuver actions are as follows: turn left, turn right, do not turn, increase speed, decrease speed, and do nothing. The velocity variations are related to the ship's traveling speed, which is specified in advance by the user. The detection region is determined by a distance (L_r) and an angle (θ_r) forward of the ship's bow, where the closest point inside this region is used for orientation. This detection region is important for avoiding the ship being locked in loops or turning when the best

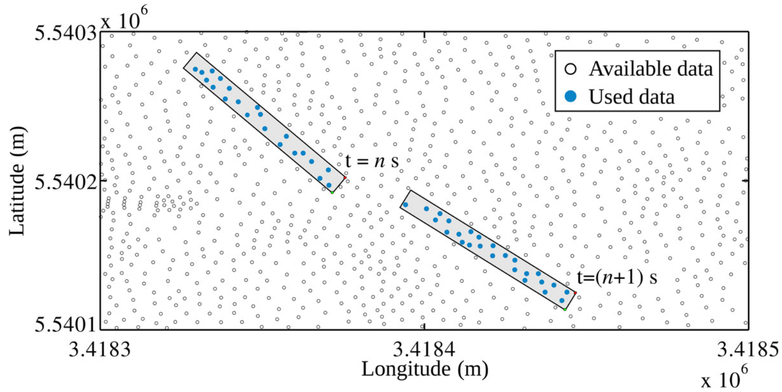


Fig. 3. Example of available (open circles) and used (filled circles) velocity points to calculate the vessel–current interaction.

move would be going forward. Fig. 5 presents an example of the points that are detected, where although points P_1 and P_2 are closer, P_3 represents a better orientation point for the ship movement direction. It is important to stress that the detection region must not be smaller than the distance between two points of the navigation path.

Successive curves over the navigation path can cause the vessel to do zigzags and, given the high inertia of ships, unnecessary maneuvers must be avoided. Therefore, other parameters and rules are used for each time step by the autopilot system, such as

- Tolerance values: If the distance of the ship to the navigation line is relatively small ($L_{\max}$; e.g., half the vessel beam) or if the ship angle is slightly different from the recommended limit ($\theta\ t_{\max}$), the autopilot does not rotate the ship. These values can be manually varied by the user in the model script;
- Response time: The user can specify a time interval in which no maneuvers take place ($R_{\max}$). For example, one maneuver action for every n seconds;
- Proportional force: The user can vary the engine force to maneuver (Fp); for example, when the ship is closer to the path, a smaller force is required to achieve a better position.

Finally, when an orientation point is detected and the autopilot rules to maneuver, the system needs to define the direction. If the vessel is in the right side of the orientation point (like P_3 in Fig. 5), the ship maneuvers to its port, and if the vessel is in the left side of the navigation path the ship maneuvers to its starboard.

Results and Discussion

During the design phase of the model, initial tests were performed for hypothetical scenarios. Several aspects were studied: ship motion, maneuverability, velocity, forces, and model stability. The software adequately represented the equations; however, oscillations in the results were identified. The model remained stable for lower values of absolute (in relation to the ground) and relative (in relation to the flow) velocity. However, when greater values of these velocities were simulated, that is, an increase of the applied engine force, the results presented oscillations whose values may or may not converge. The magnitude of these instabilities is due to the quadratic relation of the drag force with velocity. In addition, when greater time intervals were used, the drag force could reverse its direction abruptly between two subsequent time intervals; for example, when the ship velocity overcomes the flow velocity, the drag that previously pushed the ship in the navigation direction now opposes it, causing the variation in the observed results. As presented in Fig. 14, these oscillations can be reduced or eliminated by the use of a smaller $\Delta\ t$, which in turn increases the computation time. The overall model verification was performed using real data for ships navigating the Rhine river, as presented and discussed in the following section.

The Rhine River is one of the most navigated rivers in Europe and the most economically active river in Germany. The German Federal Waterways Engineering and Research Institute (BAW) is involved in all main navigational projects on this river (Zentgraf and Dettmann 2010). The middle section of the Rhine River has been extensively studied, not only because of the natural difficulties for navigation (e.g., strong currents, narrow navigation channel, intense traffic) but also because it was the site of a recent accident, as described by Harlacher et al. (2015).

The BAW made available several database files that contain the positions and times of different ships navigating two German sections of the Rhine River. The agency also shared the river bathymetry, navigation paths, and the 2D velocity field that were obtained by the use of hydrodynamic models. This data set is used in the model verification process. Fig. 6 presents a data sample, where the bathymetry was interpolated using a geographic information system (GIS) software.

For the simulated section, the ship telemetry data consisted of georeferenced points of 30 different vessels moving upstream and downstream of the waterway, with a temporal discretization of 30 s. This information allows for the calculation of several motion parameters such as the position, drift angle, and overall velocity of the ship. The mean traveling velocities of these ships are 5.6 m/s downstream and 2.7 m/s upstream of the river.

The velocity field is the result of hydrodynamic modeling of the Rhine River for different water level condition: for example, low, mean, and high water levels. The TELEMAC 2D (version 7.0) was the software used for the modeling process, and the results were high-density georeferenced points distributed within the river for a steady-state simulation. These points present information such as the magnitude and direction of the flow along the river. The flow varies in space; however, the software considers the hypothesis that no major temporal variation occurs during the ship's passage. The model is thus the steady-state result of a simulation with constant boundary conditions (invariant in time). In the studied region, the river width is approximately 650 m wide and the mean flow velocity is 1.8 m/s.

Despite the spatial constraints that are inherent in inland waterways navigation, ships can vary their routes to seek better paths: for example, greater water depth or lower or higher flow velocity. For rivers that present dense traffic, as the Rhine does, vessels have less freedom to maneuver. In order to verify optimized routes for navigation, the German Federal Agency of Waterways developed

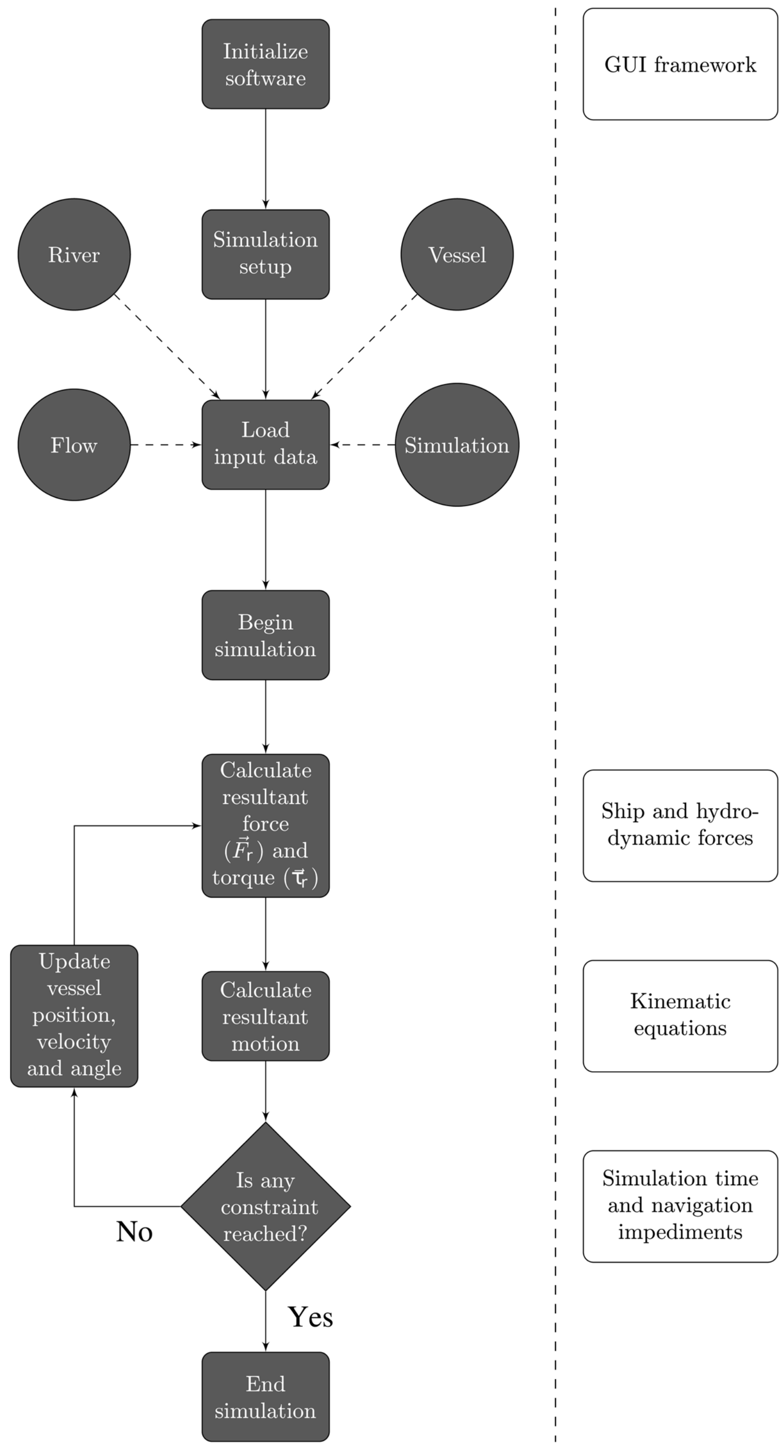


Fig. 4. Summarized algorithm diagram of the vessel–current interaction model.

techniques to define better navigation lines, so-called potential paths (Harlacher 2016a, b), for high traffic and varied environmental conditions such as low, mean, and high water levels. Two navigation paths were used in the model as references for the autopilot system: the ship passages telemetry and the potential paths.

After the setup of the main characteristics of the simulation, it is possible to use a calibration script to determine the best set of parameters that optimize navigation, as the autopilot instructions, azimuth thruster configuration, and engine force. The root mean square error (RMSE) can be used to estimate the model performance for several parameters such as path deviation, velocity, or ship angle. This approach was used to compare model results with measured data. The RMSE estimator (ϕ) is given by

$$\phi = \sqrt{\frac{1}{ni}\sum_{i=1}^{ni}(\psi m_i - \psi s_i)^2}, \qquad (5)$$

where ψm and ψs = measured and simulated parameters, respectively; and ni = number of events. One must seek the minimization

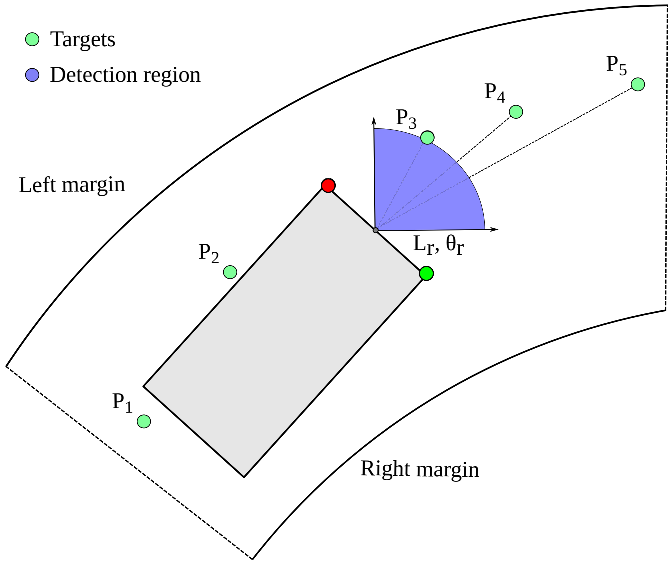


Fig. 5. Autopilot detection of the navigation channel points (targets P_1–P_5). The detection region is defined by a maximum distance (Lr) and angle (θr).

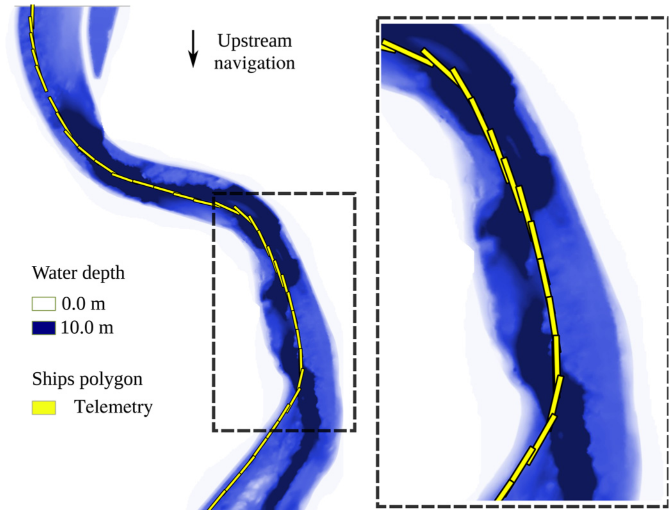


Fig. 6. Data sample shared by the BAW, containing ship telemetry and river bathymetry. Darker color represents a greater depth.

of this function because smaller values indicate that the model parameters results in a better representation of the real measurements. Currently, the ϕ parameter is being used solely for the comparison of calibration results. However, dimensionless parameters can be estimated and be used for decision-making policies.

The model capacity in reproducing the motion of real ships is a necessary indication of its performance. The first scenario used real ship passage positions as the navigation path reference points for the autopilot system, and the model results were compared with real telemetry. Then, the second scenario verified the feasibility of the potential paths. Finally, the third scenario measured the influence of the mass and velocity of vessels for navigation.

Scenario I: Ship Passage Verification

The first simulation scenario is the modeling of upstream and downstream navigation of a barge (Schubverband) for a middle water (MW) discharge level in the section between km 800 and km 805 of the Rhine River.

The model ship and simulation features are presented in Table 1. Whenever the values of total mass and engine power of a vessel is unknown, estimations of these values can be obtained by database records of the operational fleet in the region (e.g., Stichting Projecten Binnenvaart 2016) and simulations may require fine calibration to reproduce real data results. The vessel propulsion varied to reach an approximately constant velocity and the azimuth thruster force ranged between 25 and 100% of the total engine force for each simulation.

Fig. 7 presents the results for position and angle of real and simulated ships navigating downstream [Fig. 7(a)] and upstream [Fig. 7(b)] the waterway. One can observe that greater values of azimuth thruster force are required for a safe downstream navigation, where only the ships using 75 and 100% of their total maneuvering capacity were able to follow the real vessel path. For upstream navigation, ships that used 50% or more of their maneuvering capacity moved within the channel borders. These results were expected given that downstream navigation is usually associated with greater velocities, that is, there is less time to vary the

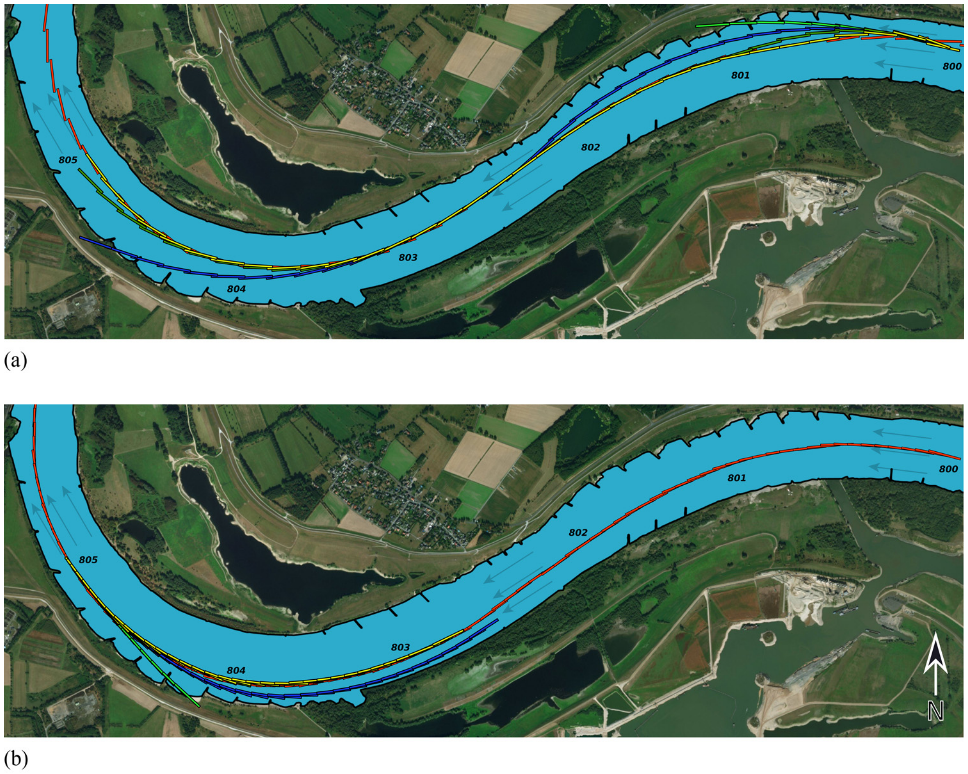
Table 1. Ship parameters setup for scenario simulations

Parameter	Description
Ship model	Schubverband
Engine power	2×103 kW
Length	200 m
Beam	12 m
Draft	3 m
Mass	5×10^6 kg
Fp	1
$L_{\max}$	6 m
$R_{\max}$	1 s
$\theta t_{\max}$	10°
Maneuver setup	Azimuth thruster, 90°
Maneuver force	(25–100%) Engine force
Simulation time	1,000 s
Simulation time step	0.1 s

angle of the ship and thus greater maneuverability capacity is required.

Table 2 shows the RMSE for the results of Scenario I. The values were compared with each Global positioning system (GPS) data time step, hence every 30 s. The error difference was smaller when greater values of maneuver force were applied for both upstream and downstream direction, which represents a better model performance. However, it is possible there is a threshold of maneuver force at which if force is increased, no advantage is obtained or the navigation is even impaired.

A detailed quantitative analysis of the model results is shown in Figs. 8 and 9, where the lines are real data values and the geometrical symbols are the model results showing downstream (Fig. 8) and upstream (Fig. 9) navigation telemetry and simulation. Figs. 8(a–c) and 9(a–c) present the position, the absolute velocity, and the bow direction, respectively, of the vessels. As also shown by visual inspection of Fig. 7 and by the RMSE analysis, the simulated vessel using 100% of possible maneuver force presented a better performance than the vessel that used only 50%. This difference was greater for downstream navigation due to the ships greater velocities. One can also observe that the upstream ship using 50% of maneuver



Telemetry 100% 75% 50% 25% Lon: 737529, Lat: 6720741

Fig. 7. Results of a ship following real data path using different maneuver forces: (a) downstream; and (b) upstream.

Table 2. RMSE results of Scenario I for position (ϕ_L), velocity (ϕ_v), and direction (ϕ_θ)

	Downstream			Upstream		
Simulation	ϕ_L (m)	ϕ_v (m/s)	ϕ_θ (deg)	ϕ_L (m)	ϕ_v (m/s)	ϕ_θ (deg)
Ship 25%	160.9	2.1	16.3	119.1	0.85	16.9
Ship 50%	105.3	1.2	14.5	54.4	0.60	8.68
Ship 75%	79.2	1.1	11.3	36.1	0.58	4.5
Ship 100%	77.1	1.4	10.3	36.3	0.58	4.4

force presented a greater resultant velocity. This is due to the fact that the vessel was further from the orientation path and closer to the river margin, where the flow velocity against the ship was lower, that is, there was less drag resistance.

Regarding Fig. 8(b), one can observe discrepancies between the model and real data velocity for the beginning and end of the section. The ship's initial speed (at km 800) was zero and some time was necessary for the ship to accelerate and achieve its travel velocity, which explains the observed difference. The velocity deviation at the end of the section is due to the autopilot algorithm. For this simulation, the model ship was configured to navigate using the real ship mean velocity; therefore, natural velocity oscillations during navigation were not represented by the model.

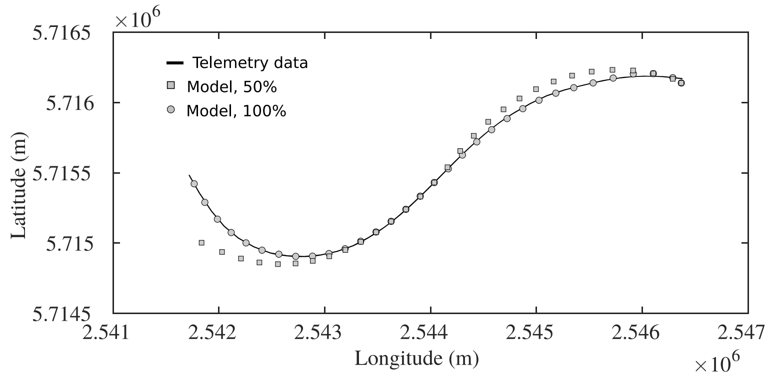
Figs. 10(a and b) present the Pearson correlation analysis for velocity and angle, respectively, between the measured and model data for downstream simulation using 100% maneuver force. The mean velocity for the model and for the measured ship was 5.3 and 5.5 m/s, respectively. Despite the close mean values of velocity ($\Delta\bar{v} \approx 3.6\%$), this relation presented a poor correlation index ($R^2 = 0.44$). On the other hand, the relation obtained for the measured and model ship angles presented a greater correlation index ($R^2 = 0.97$); that is, the model was able to perform the necessary maneuvers to maintain the ship within the preferential navigation path direction.

The correlation pattern showed in Fig. 10 was expected due to the autopilot instruction and its degree of freedom. The autopilot can change the navigation course to keep the ship as close as possible to the ideal route. In fact, that was set as its main priority. However, as previously mentioned, the variation of the engine power by the autopilot was not configured for this simulation and the propulsion varied only to achieve the desired mean travel speed. The engine power was set so that the model ship velocity reached the reference vessel mean velocity in the curves, which explains the lower correlation index for this parameter. The focus of the model was the capacity of the ships to maneuver in the curves, but by using a few instructions, it was possible to implement an autopilot response to the variations of velocity.

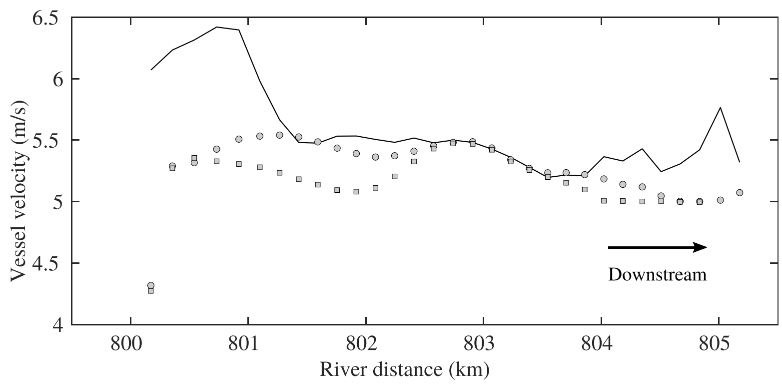
Scenario II: Potential Path Lines

In the studied section of the Rhine, ships must navigate from port to port (Pauli, unpublished data, 2013). During high water conditions (outflows between specific floodmarks at the city of Wesel at Rhine–km 813.4), the flow velocity increases up to 2.5 m/s and vessels travel near the middle of the river for safety reasons and to avoid damage to the shores caused by the impact of waves. In order to take into account an optimized navigation line while not considering encountering other ships but taking flow speeds of the river and fairway depths into consideration, the path line was calculated using the "River navigational assessment method" (RiNA) (Harlacher 2016b).

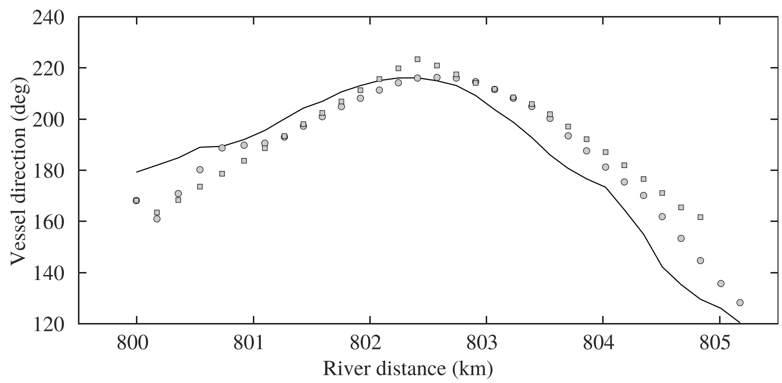
For the same set of parameters presented in Table 1 and using full azimuth thruster force to maneuver (100%), the model was applied to simulate upstream and downstream navigation using the potential lines as orientation for the autopilot. The main



(a)



(b)



(c)

Fig. 8. Downstream navigation telemetry (line) and simulation (points) results using 50 and 100% of possible maneuver force for (a) position; (b) velocity; and (c) direction.

objective of these simulations was to evaluate the feasibility of these paths for high water conditions, that is, for greater flow velocity.

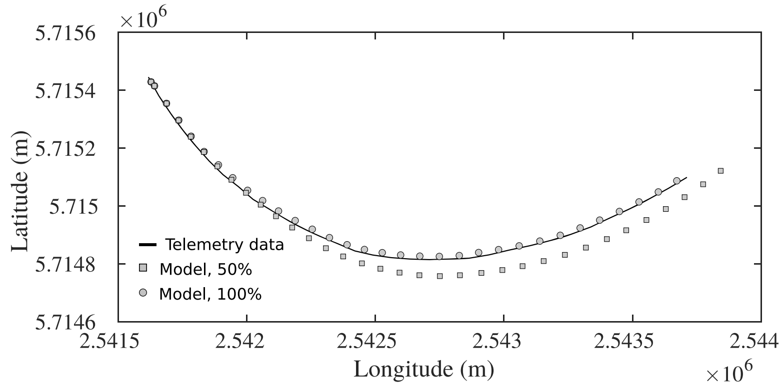
Figs. 11(a and b) present the model results for the downstream and upstream directions, respectively. For the simulated stretch, the model vessel satisfactorily navigated the river using the potential path as orientation. The vessels mostly occupied the center of the waterway, close to the desired travel line, and were thus in compliance with the high-water-condition specifications.

This navigation route is only applied during flood events and does not take into consideration encountering other vessels. The main advantage in the use of the potential paths relies on presenting the greatest depth and distance from margins. Finally, simulations for these scenarios support the feasibility analysis of new routes under severe environmental conditions.

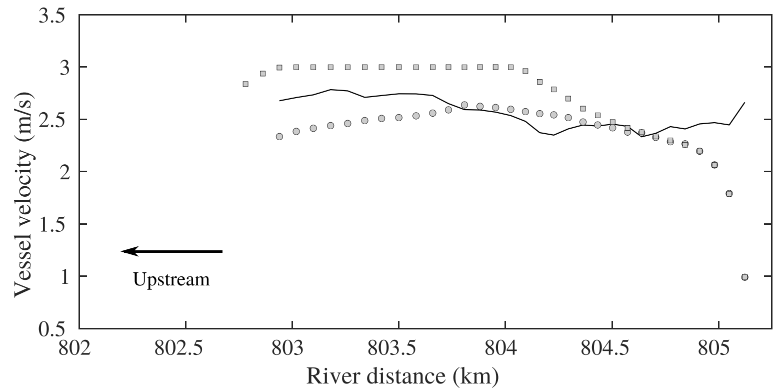
Scenario III: Mass and Velocity

This scenario presents an analysis of the relation between mass, speed, and the rotational capacity of ships for downstream navigation. The simulations also used the parameters described in Table 1, where the mass varied from 10×10^6 to 20×10^6 kg and 100% of possible maneuver force was applied. The ship passage telemetry data were used as the orientation path for the autopilot system.

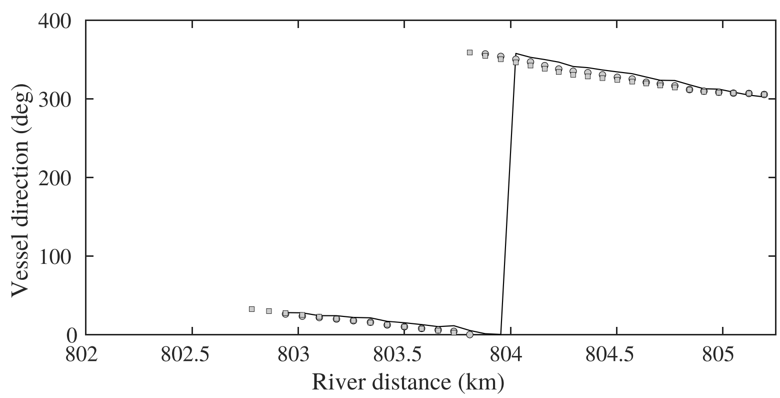
Fig. 12 shows the results for vessels with different values of mass. In Fig. 12(a), the ship velocity was unrestrained, that is, it used its total available propulsion force to accelerate. It can be seen that no ship was able to perform the curve to the port-side direction (left). When the velocity was restrained at 3.0 m/s [Fig. 12(b)], the vessel with the lowest weight remained within the channel margins. The remaining ships were not able to navigate satisfactorily with these parameters.



(a)



(b)



(c)

Fig. 9. Upstream navigation telemetry (line) and simulation (points) results using 50 and 100% of possible maneuver force for (a) position; (b) velocity; and (c) direction.

The patterns observed in the Scenario III results are due to the relation between the ship mass, the moment of inertia, the speed, and the force available for maneuvers. The moment of inertia of a body is proportional to its mass. Considering a constant angular velocity, the higher the vessel mass, the greater the force required to rotate it. Thus, for a constant azimuth thruster force, the angular variation was lower for heavier ships. When the vessel navigated at a slower translation velocity, that is, the constrained case, it had more time to maneuver, which improved the navigation.

The vessel mass values that were used are not considered feasible for daily operations: These ships usually are not loaded with such high cargo mass for safety reasons. The authors explored this simulation in order to present the effect of excessive cargo mass on navigation and highlight it here as an example of an application of the model for assessment studies and management of inland waterways.

Conclusions

The analysis of specific river parameters such as the morphology or the velocity field can provide relevant indications of its navigation capacity. Nevertheless, only by integrating these characteristics with the ship motion can a complete assessment of rivers be carried out.

The standards and guidelines are fundamental tools for the construction and operation of waterways. However, this approach may not be specific enough to optimize some inland navigation

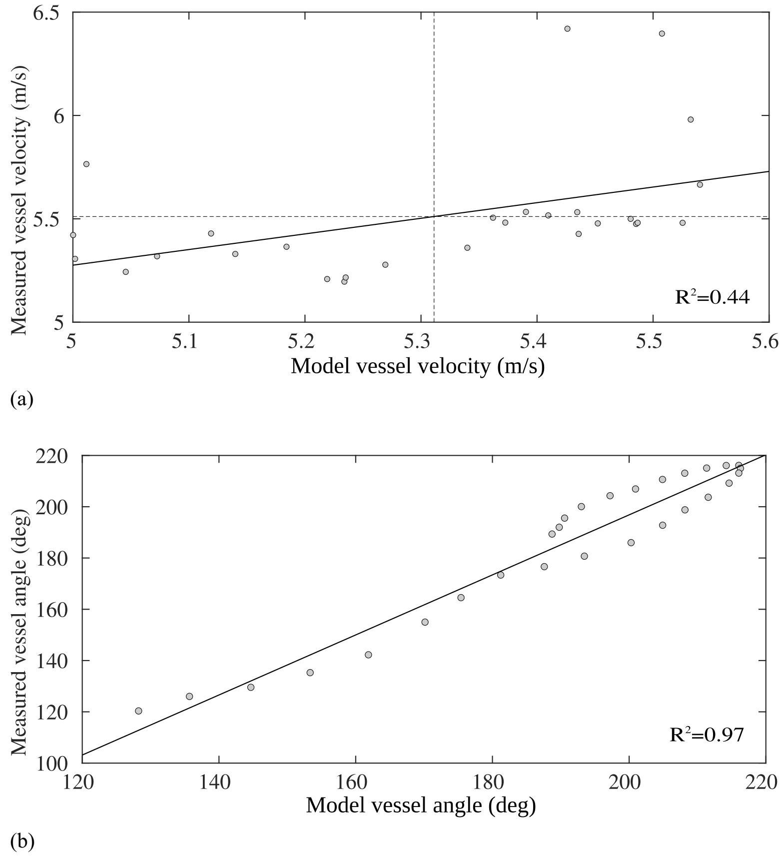


Fig. 10. Correlation analysis for (a) velocity; and (b) angle for downstream navigation of the model result and measured ship. Dashed lines indicate the parameters' mean values.

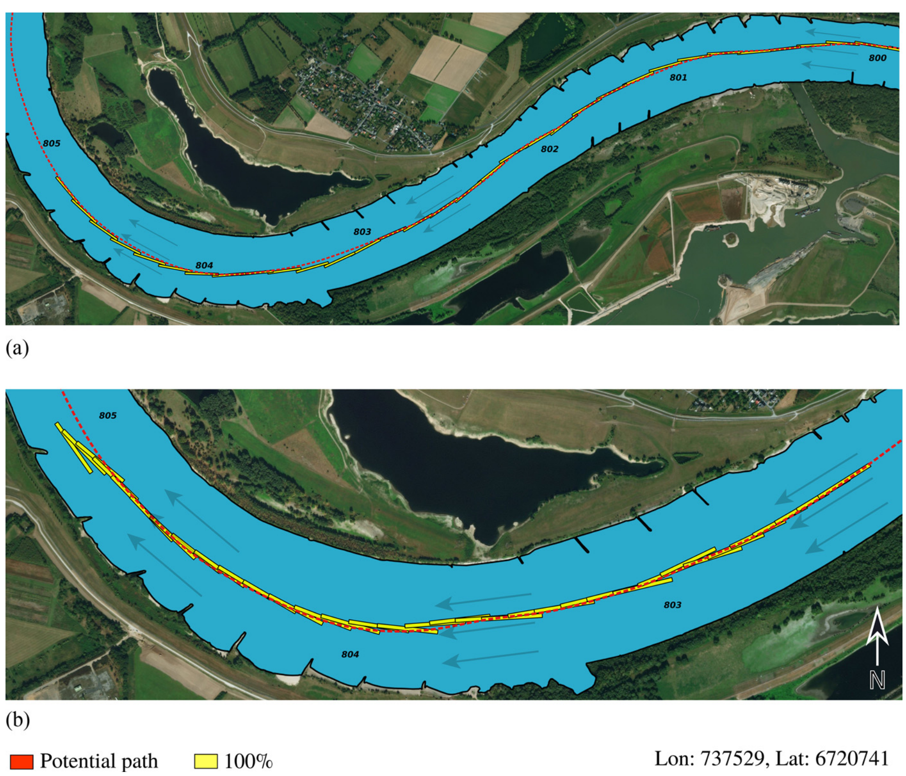


Fig. 11. Results of a ship using the potential path as orientation line: (a) downstream; and (b) upstream.

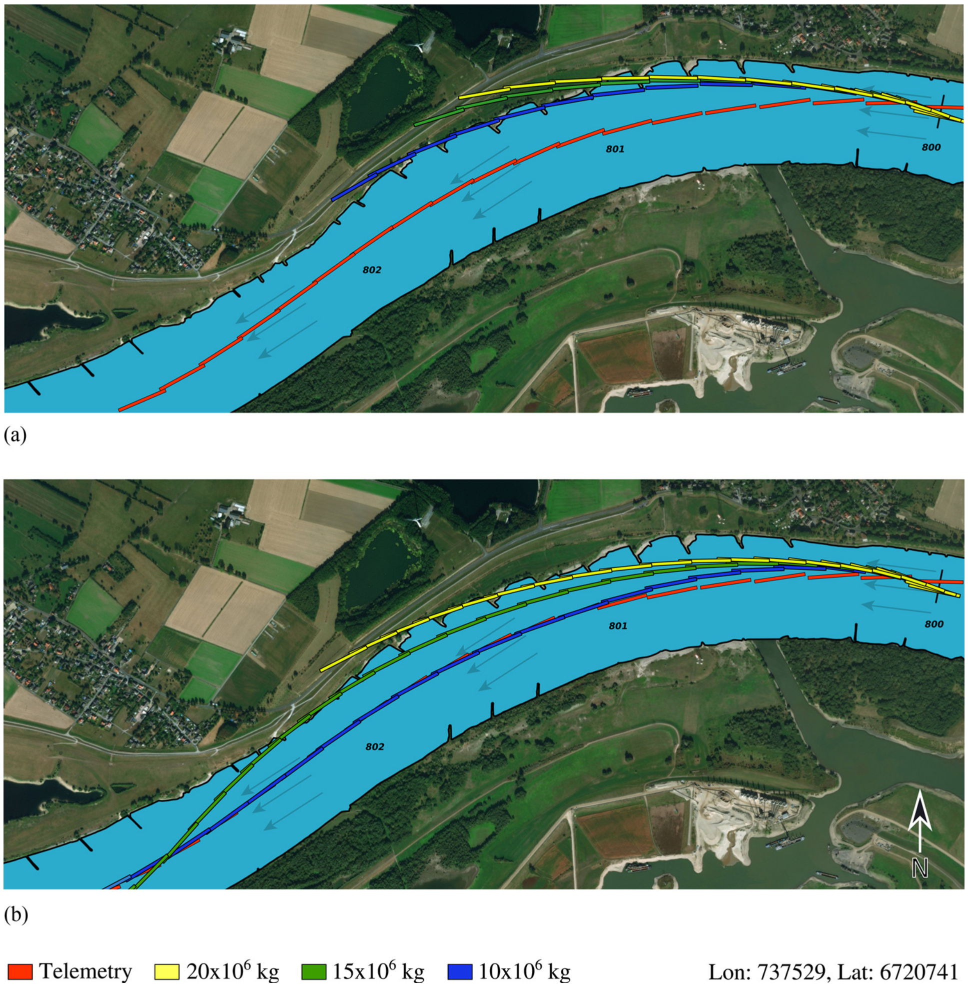


Fig. 12. Influence of speed on ship motion for different mass values: (a) unlimited; and (b) limited speed.

channels, which can lead to unnecessary adaptation and environmental impact in rivers. These analyses can be complemented by computer and scale models, which usually present a complex and expensive implementation and require a large data set and may, therefore, be unfeasible for use in the early stages of waterways studies.

The proposed 2D vessel–current model used a system of analytical equations to couple the parameters responsible for the vessel motion. This approach can be considered simpler than the use of numerical methods. Still, it allows a fast assessment using fewer data and applies to different scenarios of rivers and ships. Whenever data is available, one can easily vary project specifications and evaluate the impacts on navigation.

This model development is part of a project to better evaluate the navigability conditions of Brazilian waterways and is also being applied for studies on the Paraguay River. Due to the lack of data, a more versatile approach was required for these assessments. The partnership with the BAW allowed the model to be verified using real telemetry data of the Rhine River. These studies provided a thorough verification of the algorithm. Using the parameters of real ships, the model was able to satisfactorily reproduce the motion patterns. In addition, it was also used to validate new theoretical routes for navigation and to evaluate the influence of different parameters.

The model can be a useful tool to assist in the analysis for the construction and management of internal waterways, but its application is limited to the considered hypotheses. Thus, some aspects regarding its application are emphasized in the following:

- In relation to dimensions, the 2D approach is only valid for regions where the occurrence of waves can be disregarded. The presence of strong vertical components can generate instabilities for navigation that are not measured by the model.
- The parameters that influence the navigation must be measured in a rigorous way and avoiding subjective analysis. When vessel parameters are unknown, one can use average and typical values from databases. In addition, calibration processes can be used to enhance the results.
- The bathymetry does not directly affect the model performance; however, it should be used for the determination of the navigational channel design, that is, the orientation path. One must ensure that the simulated vessel navigates as close as possible to the orientation path to guarantee that the water level is sufficient for the passage of the ship.
- Special attention should be given to the autopilot system because there is a tendency for the use of autonomous vehicles in a near future. The autopilot can be easily improved by the addition of new maneuvering rules.
- Finally, the model is open source and one can edit or add new features in the user interface and even in the core algorithm.

This research has aspects that can be further discussed or investigated. The following points are highlighted as recommendations for future work:

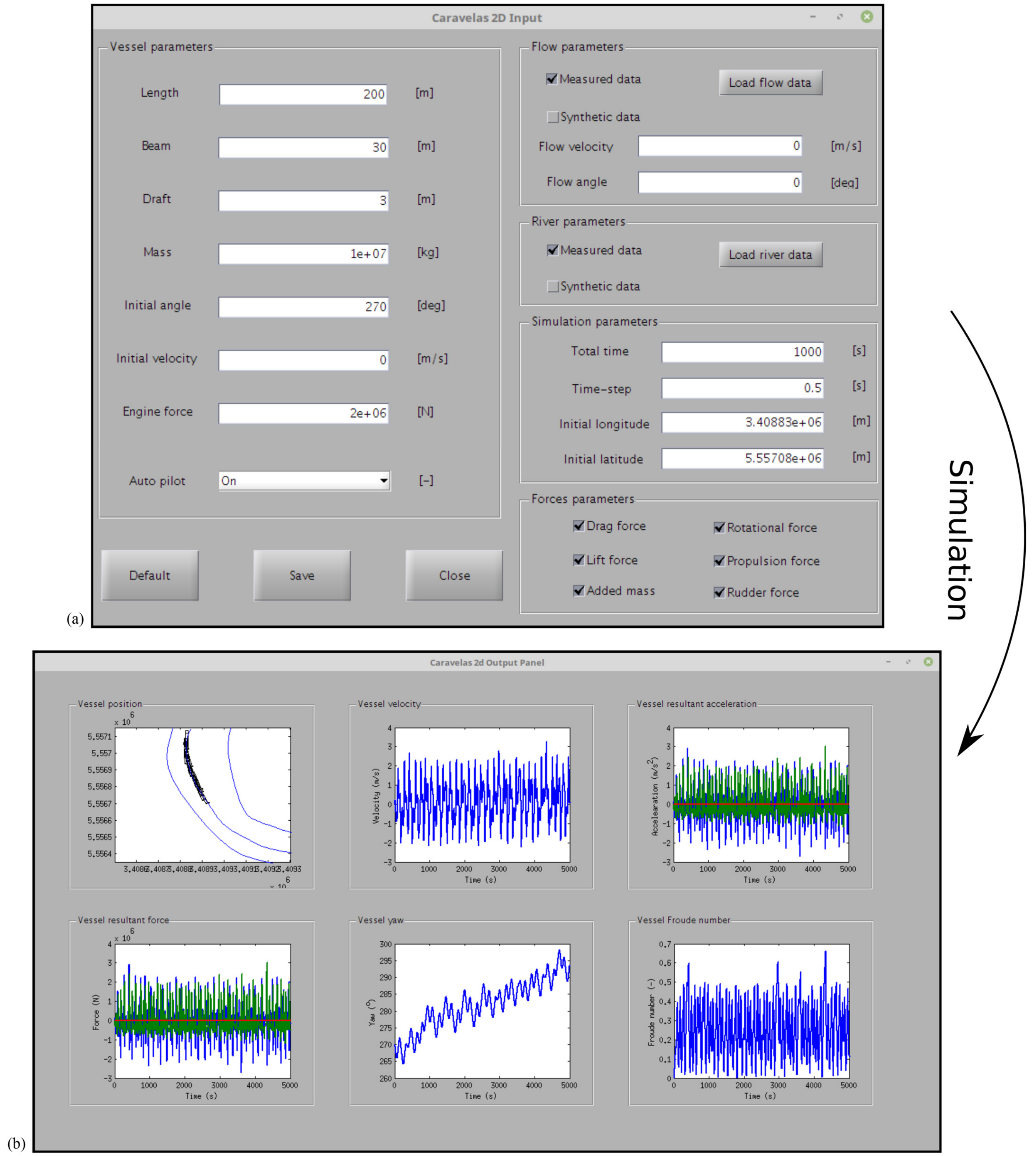


Fig. 13. Example of the model GUI to (a) setup; and (b) evaluate results.

- Research on different methods to estimate the force coefficients and to compare the model results with specific small-scale studies.
- Investigate and implement in the model the resistance effects of new forces such as wind and waves for ships navigating inland waterways.
- Study the effects on maneuverability due to ship-to-ship and to ship-to-margins separation distance.
- Use the model results (e.g., RMSE values) to vary the ship and river parameters and establish new safety thresholds for inland navigation.

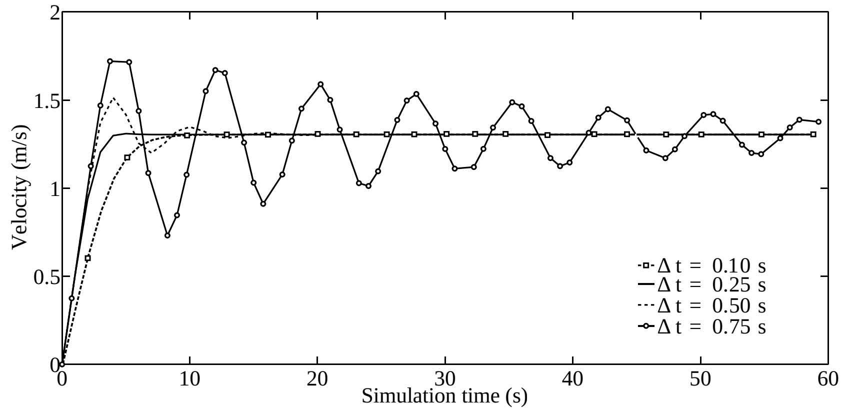


Fig. 14. Effect of the time step in the model results using a constant engine power for downstream navigation.

- Use the autopilot system and all possible river information to develop and implement a machine-learning algorithm to define the best navigation maneuvers and routes.

Appendix. Additional Figures

1. The GUI that was developed to aid the data input and results analysis of the model is presented in Fig. 13.
2. Fig. 14 presents an example of a stability analysis test performed to evaluate the model.

Notation

The following symbols are used in this paper:

α = Ship angular acceleration (m/s^2);
Δt = Simulation time step (s);
θr = Autopilot detection angle (rad);
$\theta\, t_{\max}$ = Autopilot tolerance angle (rad);
τ = Ship torque ($N{\cdot}m$);
ϕ_L = Root mean square error (RMSE) for position (m);
ϕ_v = RMSE for velocity (m/s);
ϕ_θ = RMSE for direction (deg);
ψm_i = Measured parameter value of the RMSE;
ψs_i = Simulated parameter value of the RMSE; and
ω = Ship angular velocity (rad/s).

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