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Preprint - Digital Twin and Control for Emulating Autonomous Sailboats with Conventional USVs: The Digital Sibling Concept

Loïck Degorre*, Lucia Bergantin**, Luc Jaulin* †

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Abstract

As environmental concerns and advancements in robotics continue to shape the future of marine technology, Autonomous Sailboats emerge as a promising solution for both scientific and commercial applications. Yet, testing of sensors, control algorithms, or obstacle avoidance solutions remains complex because of the fragility, cost, and difficulty of access to these systems. This work introduces the concept of *Digital Sibling*, which facilitates early Hardware-In-the-Loop testing. This technique enables the development of an experimental scheme where the complex system is simulated and its key behaviors are emulated by a simpler physical system via tracking. This novel concept, stemming from conventional Digital Twin techniques, is introduced and experimentally validated in this work. Notably, this work presents experiments where an Uncrewed Surface Vessel is used to emulate the behavior of an Autonomous Sailboat in line following, tacking and obstacle avoidance tasks.

Introduction

Advancements in robotics, coupled with environmental concerns, are increasingly shaping the evolution of marine technology. In this context, Autonomous Sailboats (ASB) emerge as an efficient, eco-friendly, and affordable solution for both scientific and commercial applications. Recent years saw the development of a growing number of applications for fully-autonomous or partly-autonomous sailboats for private navigation, cargo, or racing [1]. The economic and scientific

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benefits of research on ASBs are numerous [2]. Yet, the development of solutions specifically tailored to ASBs or Partially Autonomous Sailboats (PASB) (e.g., offshore racing sailboats with autonomous obstacle avoidance features) is hindered by numerous inherent constraints. These systems are often expensive, fragile, hardly accessible, and particularly difficult to experiment on in controlled conditions. This work presents a new tool, stemming from the concept of Digital Twins (DT), which greatly facilitates experimental testing on such complex systems and notably on ASBs.

The aim of this work is to introduce the new concept of *Digital Sibling*, which is shown to facilitate testing on ASB. The behavior of sailboats is accurately emulated using conventional Uncrewed Surface Vessels (USV) powered by electric thrusters. The problem is considered from a control perspective. The USV is controlled to track an ASB that is simulated in real time. The USV mimics key aspects of the behavior of the ASB, as the latter evolves in controlled conditions in the simulation. The USV sends sensor data back to the ASB simulation (e.g., to populate the simulated environment with real obstacles or to incorporate weather measurements into the simulation). This technique facilitates Hardware-In-the-Loop (HIL) testing on complex systems such as ASBs, enabling the evaluation of key components, sensors, or algorithms on an easily accessible system.

The *Digital Sibling* scheme enables the physical system to emulate the digital system's behavior, or at least key aspects of it. For instance, one particular feature of sailboats is the need for tacking when going upwind. When testing sensors, obstacle detection methods, control algorithms, or obstacle avoidance solutions, it is mandatory to assess the interaction of the system with tacking.

Related Works

The concept of *Digital Sibling* stems from conventional DT technology. In DT techniques, two copies of the same system are considered: one simulated or *digital*, and one *physical*. Any modification of one is replicated by or applied to the other. This principle was developed for industrial applications in the 90s and is considered a major component of Industry 4.0. The first conceptualization of DT is commonly attributed to Grieves in the early 2000s [3]. Yet, several prior applications of similar techniques can be found, notably led by NASA during the Apollo 13 missions and referred to, at the time, as mirroring systems. In the 2010s, NASA described DT as a major and key subject for the following years [4].

The work of [5] gives an overview of DT technology in various applications. DT is now used in a wide number of domains in industry like designing, planning, optimization, maintenance, safety, decision-making, or training [6]. A small number of studies have also proposed applications of DT for control tuning of systems [7]. The work of [8] gives a classification of DT applications. However, the number of examples of DT applications in the marine context remains scarce [9, 10].

Two key components can be identified in most DT techniques proposed in the literature:

1. Two identical systems operating in tandem: a digital one, which is simulated, and a physical one,
2. A two-directions data flow between the two systems.

In terms of control, few studies explicitly deal with the question of closing the loop between the digital and physical twins to ensure exact reproduction of the behavior of one by the other. This is the main focus of our work. Note however that the works of [11, 12] present control schemes for DT applications where the digital twin tracks the physical twin but rarely the opposite.

As will be seen in the following, this work deviates from the traditional concept of DT. Here, two systems are considered that are not exact replicas of one another, approaching the problem from a control engineering perspective. This differs from most approaches, usually based on Internet of Things or Artificial Intelligence technology. The concept proposed in this work is, to the authors' best knowledge, a novel contribution, and no relevant or similar work has been found using the same technique.

Contributions

The concept presented in this work finds its roots in DT technology, but differs in several aspects. First, because the two systems at hand are not exact replicas of one another: they are *siblings* and not *twins*. The two systems share similarities and might belong to the same class of systems, yet they are not identical. This paper thus introduces the concept of *Digital Siblings*.

To demonstrate the interest of this concept, this work presents an experimental application where the *Physical Sibling* (PS) is a USV and the *Digital Sibling* (DS) is an ASB. Experimental results on two typical missions are given to demonstrate the interest of the concept.

The contributions of this work can be summed up as:

- Introduction of the concept of *Digital Sibling*,
- Presentation of experimental results validating the concept on the USV-ASB application.

Outline

The outline of this work is as follows. Section 1 presents preliminaries to this work, notably the sailboat dynamic model and the two controllers. Section 2 details the main contribution of this work : the description of the concept of *Digital Sibling*. Section 3 presents experimental results obtained on the USV-ASB application. Section 4 gives conclusions on this work and perspectives for future works.

1 Preliminaries

This section describes the dynamic model of the sailboat used for the simulation of the DS. It also introduces the sailboat line-following controller, as well as the trajectory tracking controller of the USV.

1.1 Model of the Simulated ASB

For a realistic yet simplified simulation of the ASB, a complete dynamic model of an autonomous sailboat is implemented in *Python 3.0* using the *Robot Operating System (ROS)*¹. For the first application of this concept, a simplified simulator was used, which does not account for complex environmental phenomena. Further analysis with a more physically realistic simulator should be conducted. All the nodes of this application are designed to run on a *RaspberryPi4* onboard computer.

The dynamic model of the sailboat is:

$$\begin{aligned}
 \dot{x} &= v \cos \theta + p_1 a_{tw} \cos(\psi_{tw}) \\
 \dot{y} &= v \sin \theta + p_1 a_{tw} \sin(\psi_{tw}) \\
 \dot{\theta} &= \omega \\
 \dot{v} &= \frac{f_s \sin(\delta_s) - f_r \sin(\delta_r) - p_2 v^2}{p_9} \\
 \dot{\omega} &= \frac{f_s(p_6 - p_7 \cos(\delta_s)) - p_8 f_r \cos(\delta_r) - p_3 \omega v}{p_{10}}
 \end{aligned} \tag{1}$$

with:

- x, y : position of the center of the ASB in the North-East-Down (NED) reference frame
- θ : heading angle
- p_1, \dots, p_{10} : parameters of the sailboat (see [13] for the complete set of parameters),
- v : forward speed,
- ω : angular speed,
- δ_s : sail angle,
- δ_r : rudder angle,
- $f_s = p_4 \|a_{aw}\|^2 \sin(\delta_s - \psi_{aw})$: force of the wind on the sail (with a_{ap} apparent wind speed and ψ_{aw} apparent wind angle),
- $f_r = p_5 v \sin(\delta_r)$: force of the water on the rudder.

¹<https://www.ros.org/>

The inputs of the dynamic model (1) are (i) the rudder angle δ_r and, because the sail sheet is flexible, (ii) the maximum sail trim angle δ_s^{max} .

The simulated sailboat is considered to be equipped with (i) a Global Navigation Satellite System (GNSS), (ii) a compass, and (iii) a weather station measuring the angle and speed of the wind.

1.2 Controller of the ASB

The guidance principle, controller, and obstacle avoidance algorithm used on the ASB in the following experiments are described in detail in [14]. They are only briefly recalled here.

The sailboat performs a line-following mission. For guidance, a reference heading angle is calculated in conventional Line Of Sight fashion [15]:

$$\theta_d = \phi - \arctan\left(\frac{e}{r}\right) \quad (2)$$

where ϕ is the angle of the reference line, e is the distance between the ASB and the line, and r defines an air corridor around the line. Note that the arctan function can be replaced with `arctan2`² to avoid singularities.

In the vicinity of obstacles, the reference heading angle θ_d is updated following the Artificial Potential Field described in [13].

If θ_d is within a zone of angle ζ around the direction of the wind ψ_{tw} (the so-called dead zone), it is not considered a feasible heading for the sailboat. Under such circumstances, the ASB must tack. The reference heading is updated as:

$$\theta_d = \psi_{tw} - \pi - q\zeta \quad (3)$$

where q is a hysteresis variable equal to $+1$ or -1 . The hysteresis q switches value every time the ASB exits the air corridor defined with r . In the following experiments, the size of the corridor is $r = 10$ m and the close-hauled angle is $\zeta = 35^\circ$.

Then, two proportional correctors are used to compute the rudder and maximum sail angles:

$$\delta_r = \frac{\Delta_r^{max}}{\pi} \text{sawtooth}(\theta - \theta_d) \quad (4)$$

$$\delta_s^{max} = \frac{\pi}{2} \left(\frac{\cos(\psi_{tw} - \theta_d) + 1}{2} \right) \quad (5)$$

where Δ_r^{max} is the maximum rudder angle. The sawtooth function ensures that the angle difference is defined between 0 and 2π .

1.3 Controller of the USV

In this work, the goal of the USV is to track one output of the ASB. Notably, in this work, the USV tracks the position of one sensor equipped on the virtual ASB (see Section 2 for more details about the output choice).

²<https://numpy.org/doc/stable/reference/generated/numpy.arctan2.html>

From the point of view of the USV, tracking the position of the DS is no different from a conventional trajectory tracking mission. At each time step, the state of the ASB gives the new reference of the controller. In this application, the controller node and the ASB simulation node are running at the same frequency, meaning that there is one new position reference for each control calculation. Further work will study the consequences of having different frequencies and go deeper into the side effects generated by the hybrid continuous-discrete systems.

Note that the USV used in this work, a *BlueBoat*³, features an autopilot control board including a dynamic controller. Hence, the inputs of the USV are the surge and yaw speeds. The autopilot theoretically ensures convergence of the actual speeds of the craft to the references.

For this example, the Kinematic Guidance Principle (KGP) introduced in [16, 17] and lately in a simpler form in [18], is used for the control of the USV. In KPG, instead of controlling the center of the craft, which is singular, a different point is selected (the tracking point) and controlled toward a given reference. The main interest of using an off-centered point is that the controller can be shown to asymptotically stabilize this point to the reference without singularities. Also, considering the application of this work, the controller is particularly suited for positioning in space a given sensor equipped onboard the USV as if it were equipped onboard an ASB.

Let us introduce the kinematic model of the USV:

$$\dot{x} = u \cos \psi + v \sin \psi \quad (6a)$$

$$\dot{y} = u \sin \psi - v \cos \psi \quad (6b)$$

$$\dot{\psi} = r \quad (6c)$$

where $[x, y]^T$ is the position of the center of the USV in the NED frame, ψ its heading, and u , v and r are the surge, sway, and yaw speeds in the body-fixed frame, respectively. u and r are the inputs of the kinematic system (6a).

The position of the tracking point E , considered as the output of the controller, in this case is:

$$\mathbf{Y} = \begin{bmatrix} x_E \\ y_E \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} \quad (7)$$

where $[\varepsilon_x, \varepsilon_y]^T$ is the position of the tracking point in the body-fixed frame.

The first time derivative of \mathbf{Y} can be written as:

$$\dot{\mathbf{Y}} = \mathbf{M}\mathbf{U} + \mathbf{N} \quad (8)$$

³<https://bluerobotics.com/store/boat/blueboat/>

with:

$$\mathbf{U} = \begin{bmatrix} u \\ r \end{bmatrix}, \quad \mathbf{M} = \begin{bmatrix} \cos \psi & -\varepsilon_x \sin \psi - \varepsilon_y \cos \psi \\ \sin \psi & \varepsilon_x \cos \psi - \varepsilon_y \sin \psi \end{bmatrix},$$

$$\mathbf{N} = \begin{bmatrix} -v \sin \psi \\ v \cos \psi \end{bmatrix}.$$

Matrix \mathbf{M} is invertible for any off-centered tracking point (that is $\varepsilon_x \neq 0$) and ψ and v are accurately measured on the USV. Hence, an intuitive controller is derived:

$$\mathbf{U} = \mathbf{M}^{-1} (\mathbf{V} - \mathbf{N}) \quad (9)$$

where $\mathbf{V} = [V_x, V_y]^\top$ is a new input. The controller (9) cancels the nonlinearities of the system (8). Any conventional stable linear regulator for \mathbf{V} ensures convergence of the output towards the reference. Notably, in this work, two decoupled Proportional Integral (PI) controllers are used for V_x and V_y .

2 The Digital Sibling Concept

This section presents the main contribution of this work: the introduction of the concept of *Digital Sibling*. This concept is built upon the same foundation as classical DT theory. Here, the two systems, the *Digital Sibling* (DS) and the *Physical Sibling* (PS), need not be exact replicas of each other. The two siblings can be any pair of systems sharing at least one common output. The PS tracks or reproduces one output of the DS and captures one (or several) key characteristic(s) of the behavior of the DS. Applications of the DS concept include testing sensors whose performance is impaired or affected by a specific aspect of the DS, as well as testing control strategies to stabilize a specific output and observe its behavior.

For a clearer explanation of the DS concept, the following description takes the case of the USV and ASB as an example. An USV (the PS) is used to reproduce the behavior of an ASB (the DS).

The common output chosen is the position of a given point on each vehicle. This choice allows capturing the behavior of a sensor placed onboard the ASB, which is the main goal of this experiment. In particular, we focus on testing obstacle detection sensors and more specifically an intelligent camera package⁴, in complex maneuvers of the sailboat, such as tacking and obstacle avoidance routes. Tacking is a major feature of the behavior of the ASB sailing upwind that the USV, as the PS, must be able to capture.

Note, however, that several choices can be made for this pair of systems. To test control systems or obstacle avoidance strategies, for instance, choosing the surge speed and heading of the craft as the output could be interesting. Yet,

⁴For instance, obstacle detection package developed by the *SEA.AI* company <https://www.sea.ai/>, with which the authors collaborate.

this choice would not capture side slipping, which is an important part of the behavior of a sailboat.

In general, a few rules of thumb can be traced to direct the choice of the common output:

- The dimension of the common output must be smaller than or equal to the dimension of the input of the PS (usually given by the number of actuators),
- The output must be measurable or observable on the two systems,
- The output must be controllable⁵ at least on the PS.

The choice of the output is limited by the capabilities of the PS. Here, the USV is underactuated and only able to track an output of dimension two. To add a new component to the tracked output, a new actuator must be added to the PS. However, this new actuator must not necessarily be a new thruster. To add the heading of the ASB (or any related angle, like the direction of acquisition of a camera) as a new tracked output component, a servo would be sufficient. In this example, because of sideslip, the heading of the ASB and the heading of the USV cannot be the same. In order to experiment with a camera detecting obstacles, for instance, the camera could be mounted on the USV on a rotating gantry tracking the heading of the ASB. This would allow respecting the inherent constraints of the USV while adding a new dimension to the experiment.

Moreover, one important feature of the DS concept is the two-directional flow of information between the PS and the DS, much like conventional DT. On the one hand, the output of the DS is communicated to the PS and used as a reference in the PS controller. On the other hand, data from sensors equipped on the PS is communicated to the DS and used to update the simulation. For instance, when USV sensors detect an obstacle, the position of the obstacle is duplicated in the simulation. The DS then initiates the obstacle avoidance maneuver, and the PS follows.

3 Experimental Results

This section presents the experimental results obtained with the DS approach on the USV-ABS example. In these experiments, the ASB is simulated and controlled to follow a line or series of lines. The missions of the ASB are defined in the physical world in latitude and longitude coordinates and replicated in the simulation using GNSS data furnished by the physical USV. During the mission, the position and speed of the ASB are communicated to the USV and expressed in a local Lambert frame common between the two systems and initiated on the first position of the USV.

⁵Here, *controllable* is used in a broad sense. The PS must be able to act on the output and stabilize it to a given reference value with a controller and, if needed, guidance principle.



Figure 1: The *BlueBoat* sailing on the lake of Guerlédan (Brittany, France) during one of the experiments.

Two missions were assessed in this work. First, a triangular trajectory is tested in two different wind conditions. Then, one example of obstacle avoidance is tested. The goal of these experiments is to illustrate the emulation of the behavior of the ASB by the USV, notably sideslip and tacking when sailing upwind.

These experiments were performed on the lake of Guerlédan (Brittany, France). On the test day, the conditions on the lake were ideal, with almost no wind or current, which allowed for a good first test of the DS principle. For these tests, the tracking point was placed 1 m from the center of the boat ($\varepsilon_x = 1$, $\varepsilon_y = 0$) and materialized with a pole as seen on Fig. 1.

3.1 Line Following Experiments

In these experiments, the ASB follows a series of three lines defined with a set of fixed GPS coordinates. A first segment is added to connect the initial position of the USV with the starting point of the triangle. The goal of these tests is twofold: (i) validate the behavior of the simulated ASB in different wind conditions, and (ii) validate that the perceived behavior of the USV captures the key characteristics of the ASB we aimed to reproduce (notably tacking and sideslip).

A top view of the position of the tracking point of the USV (in orange), the

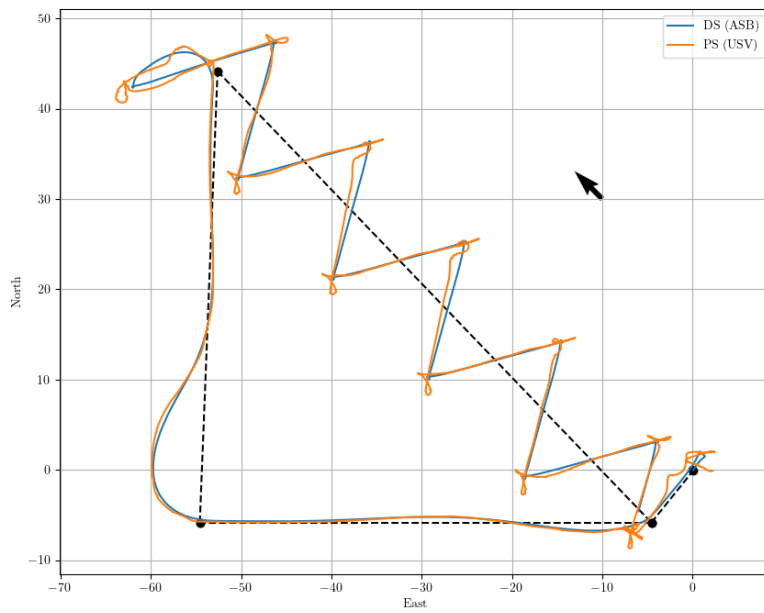


Figure 2: Top view of the first triangle mission with South-East wind (indicated by the black arrow). Dashed black line: reference trajectory given to the ASB.

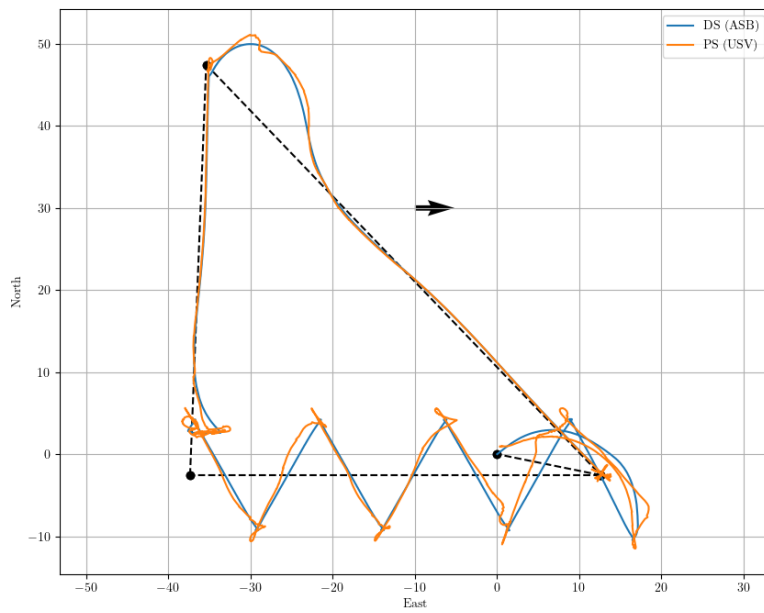


Figure 3: Top view of the second triangle mission with West wind (indicated by the black arrow). Dashed black line: reference trajectory given to the ASB.

simulated ASB (in blue), and the desired lines and checkpoints (black dashed line and dots) for the two triangle missions can be seen on Fig. 2 and Fig. 3.

These two experiments validated the behavior of both the ASB and the USV. On a first test illustrated in Fig. 2 under South-East wind conditions, the ASB sailed Broad Reach (wind angle of about 135°) on the first East to West segment, maneuvered once before converging back to the line, and kept sailing Broad Reach on the South to North segment. The ASB then entered a new maneuver to start on the North-West to South-East segment. On this last segment, the ASB was required to sail directly upwind and had to perform a succession of tacking maneuvers.

Similar results were observed for the second test under West wind conditions depicted on Fig. 3. This time the first segment was upwind and the ASB tacked, while the second and third segments were Beam Reach (wind angle of about 90°) and Broad Reach, respectively. One can notice a short mishap at the transition between the first and second segments. The ASB validated the second checkpoint in the middle of its last tacking maneuver. The sudden change of requested heading led to a short drifting period while the ASB was directly facing the wind and had to accelerate again before being able to transition to the second segment.

About the behavior of the USV, Fig. 2 and Fig. 3 show very good tracking of the position of the ASB with the tracking point. The PS did capture the behavior of the DS. Notably, it accurately reproduced the tacking maneuvers and the sideslip during the changes of direction. The behavior of the ASB was successfully and convincingly emulated.

However, one can observe that, during hard turns and notably during tacking maneuvers, the USV struggled to maintain good tracking. In fact, from a control perspective, the trajectory of the ASB is almost discontinuous. When tacking, the ASB stopped and turned on the spot, leading to very steep variations in the reference given to the controller of the USV. In trajectory tracking, it is common practice to consider a continuous and sufficiently regular reference trajectory to establish the controller and show its stability. Here, the trajectory of the ASB is at the limit of this assumption because of the steep turns. Also, Fig. 4 compares the command speed calculated by the controller u_1 and u_2 (in blue on the two graphs) with the actual surge and yaw speeds u and r (in orange) during the first triangle trajectory, and shows that the onboard autopilot introduces latency and marginal errors in the application of the control. This participates in the tracking artifacts observed on Fig. 2 and Fig. 3.

3.2 Obstacle Avoidance Experiment

This experiment highlights the main interest of the DS approach. Here, the goal is to evaluate the behavior of the sailboat in obstacle avoidance maneuvers, and to validate the idea of a DS-based HIL testing approach. In further works, such experiments would allow fine-tuning the obstacle detection sensor package, the avoidance algorithm, and studying the behavior of the system when, for instance, the maneuvers of the ASB cause the obstacle to move out of the

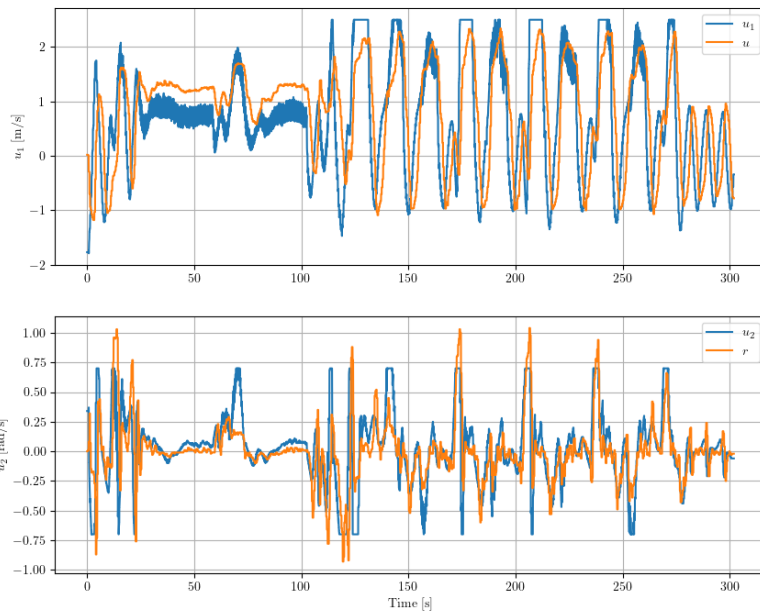


Figure 4: Comparison of the command speeds calculated by the controller (in blue) with the actual surge and sway speeds (in orange) on the first triangle trajectory.

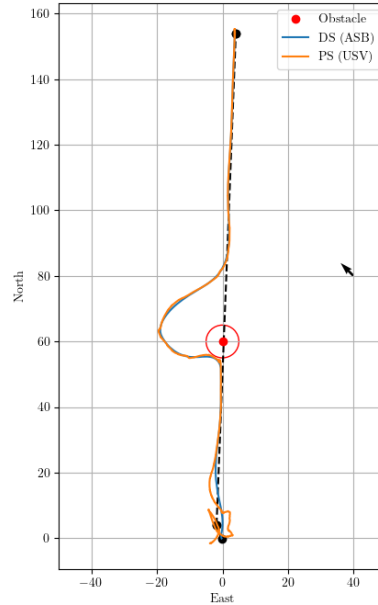


Figure 5: Top view of the obstacle avoidance mission with South-East wind. Dashed black line: reference trajectory given to the ASB; Red dot: Obstacle; Red circle: Obstacle detection range.

sensors' field of view.

The obstacle detection camera package was not accessible for this experiment. The obstacles were virtual and simulated with fixed areas on the lake. Their positions were considered known, but they were only detected by the USV once it entered the detection area (materialized with the red circle on Fig. 5, radius 10 m). Once an obstacle was considered as detected, the simulation of the ASB was updated. The obstacle was automatically added to the virtual world of the DS and was detected by the ASB. The ASB then initiated an obstacle avoidance maneuver, following the Artificial Potential Field presented in section 1.2. Fig. 5 shows that the USV followed the maneuver of the ASB and both systems converged back to the line once the obstacle was cleared. This experiment confirms that the DS approach is well suited for this type of tests.

4 Conclusions and Future Work

This work introduces the concept of *Digital Sibling* for early testing of complex systems in controlled conditions. Experimental results on the example of a physical USV reproducing the behavior of a simulated ASB are produced. Our findings show that the concept, methodology, and controllers proposed in this work are well suited for capturing the key aspects of the behavior of a complex system (here the ASB) and reproducing it with a simpler and more accessible one (the USV). Notably, it is shown that the USV reproduces tacking maneuvers and side slipping that are typical of sailboats.

We noticed that the limited maneuverability of the chosen USV platform diminishes the quality of the emulation. Also, the relatively small scale of the vehicles considered in this work leads to the limits of some much-needed assumptions, notably regarding the necessary smoothness of the trajectories considered when establishing the trajectory tracking controller. Yet, it is expected that with larger scale systems, these almost-discontinuities will naturally be smoothed out. Also, the latency introduced by the USV's autopilot highlights the need for complete control of the dynamics of the PS.

This project was a first step in the *Digital Sibling* world. Further works have already been initiated to push the concept forward. Notably, future projects will study the consequences of running two systems with different time scales in parallel. If a more powerful simulation of the DS were needed, the data flow between the two systems would slow down and the overall system would become a hybrid continuous-discrete one with associated constraints. The PS controller would need to be updated, and so would the flow of data going back to the DS. Similarly, future work will analyze the consequences of having additional, potentially more complex sensors with lower acquisition frequency, particularly for obstacle detection.

Additionally, efforts will be made to test this strategy with other pairs of systems (e.g., a fully-actuated underwater robot mimicking the behavior of an autonomous glider or a flying quadrotor emulating the behavior of a camera placed at the top of the mast of a sailboat). Future work will also lead to a qualification of different pairs of systems; some pairs of simple systems (e.g., linear or feedback linearizable ones), may not require a real-time simulation of the DS, and the conception of specific controllers would be enough to input the dynamics of the DS into the behavior of the PS.

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