Emulating the behavior of an autonomous sailboat: Real-Time Digital-Twin Controller

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Context

/ Developing obstacle avoidance solutions for autonomous sailboats

/ Developing piloting assistance for racing IMOCA sailboats with *Pixel sur Mer*

↓

Use of a **digital twin framework** to **facilitate testing** of **sensors** and algorithms using a **conventional USV reproducing the behavior of a sailboat**

State of the Art

→ Control via Real-Time Digital Twin in the Marine Context

/ The concept of Digital Twin: *M. Singh et al.* ***Digital Twin: Origin to Future****, ASI 2021*

"A Digital Twin is a dynamic and self-evolving digital model of a real-life subject […] representing the exact state of its physical twin […] via exchanging the real-time data as well as keeping the historical data..."

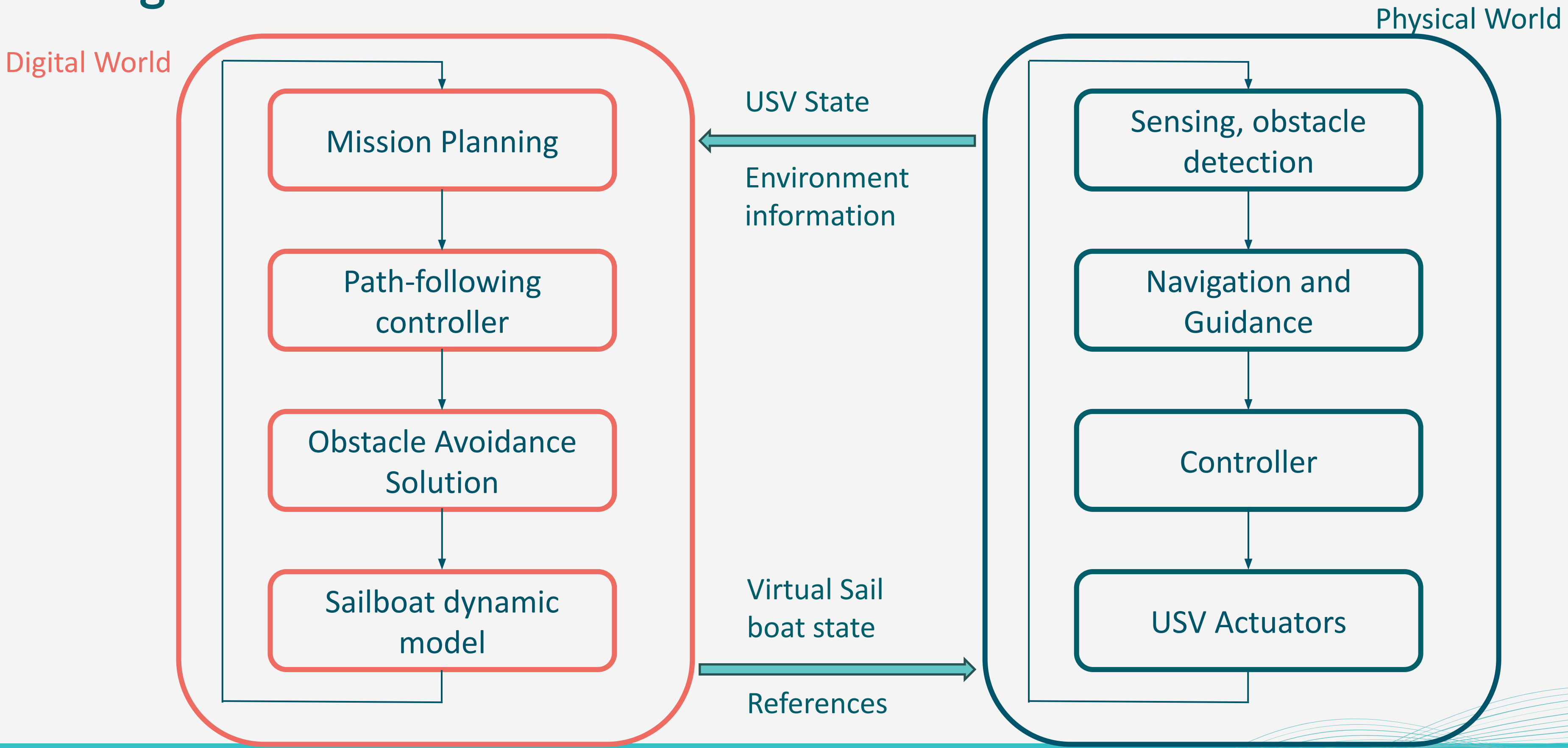
/ Few occurrences of digital-twin driven control in the marine context in literature

- *Lee et al.* ***Ship digital twin architecture for optimizing sailing automation****, OE 2022*
- *Kinaci* ***Ship digital twin architecture for optimizing sailing automation****, OE 2023*

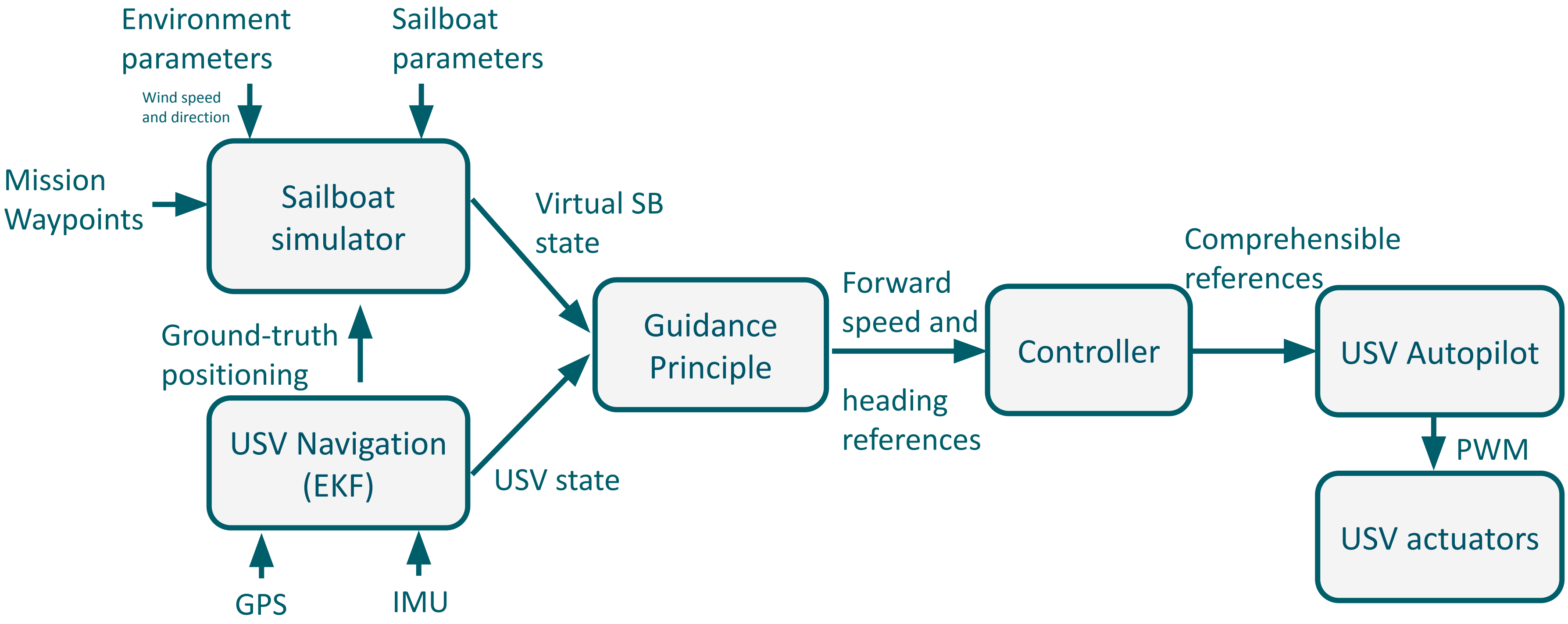
/ Several examples of digital-twin control applications outside the marine field

- *He et al.* ***Digital Twin-Driven Controller Tuning Method for Dynamics****, JCISE, 2021*
- *Armendia et al.* ***Twin-Control Approach****, Springer, 2019*

The Digital Twin framework



Today's focus : The USV Control Structure



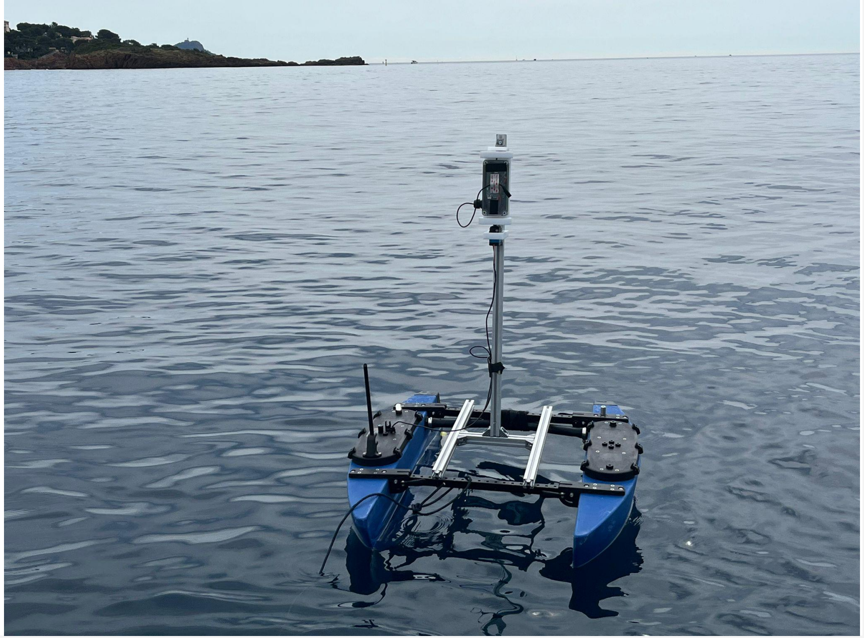
The USV : Bluerobtic's BlueBoat

/ Native features

- GPS
- IMU
- EKF
- Low-level autopilot
- Two M200 Thrusters

/ Additions

- Mast, camera and pan mechanism
- RC controller



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Sailboat Simulator

/ Simulation of the sailboat on a path following task going upwind.

/ The simulator considers the dynamics of the craft, the sail and the rudder.

/ The boat starts tacking when it reaches the far end of the corridor around the desired path.

Sailboat Simulator
-> Autonomous sailboat path following controller

$$e = \det\left(\frac{\mathbf{b}-\mathbf{a}}{\|\mathbf{b}-\mathbf{a}\|}, \mathbf{m}-\mathbf{a}\right)$$

$$\text{if } |e| > r \text{ then } q = \operatorname{sign}(e)$$

$$\varphi = \operatorname{angle}(\mathbf{b}-\mathbf{a})$$

$$\bar{\theta} = \varphi - \operatorname{atan}\left(\frac{e}{r}\right)$$

$$\text{if } \cos\left(\psi - \bar{\theta}\right) + \cos\zeta < 0$$

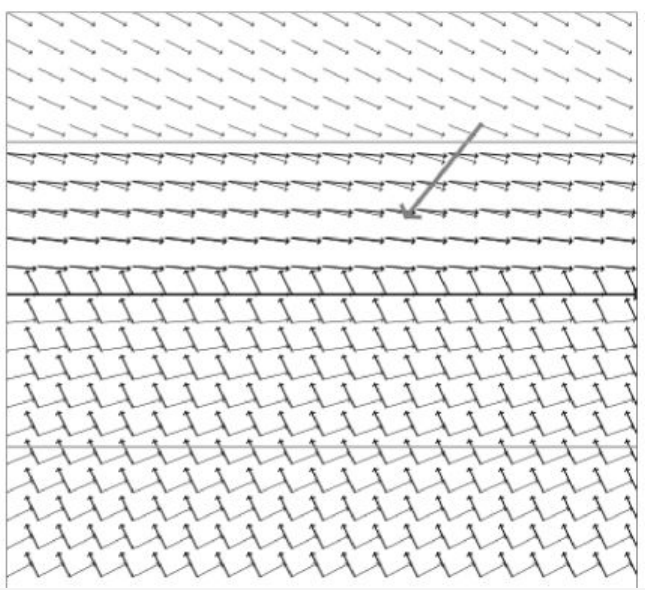
$$\quad \text{or } \left(|e| - r < 0 \text{ and } \left(\cos(\psi - \varphi) + \cos\zeta < 0\right)\right)$$

$$\quad\quad \text{then } \bar{\theta} = -\psi - q\zeta.$$

$$\delta_r = \frac{\delta_r^{\max}}{\pi} \operatorname{sawtooth}(\theta - \bar{\theta})$$

$$\delta_s^{\max} = \frac{\pi}{2}\left(\frac{\cos\left(\psi - \bar{\theta}\right)+1}{2}\right)^{\frac{\log\left(\frac{\pi}{2\beta}\right)}{\log(2)}}$$

Sailboat control algorithm - ***Robmooc***, *L. Jaulin*



Vector field created by the controller

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Sailboat Simulator
→ Obstacle avoidance strategy

- Artificial vector field strategy
- The vector field represents the ‘safest’ way to avoid the obstacles
- Obstacles create a high potential repulsive field
- The boat stabilizes parallel to the line while in range of an obstacle, then converges back to the line.

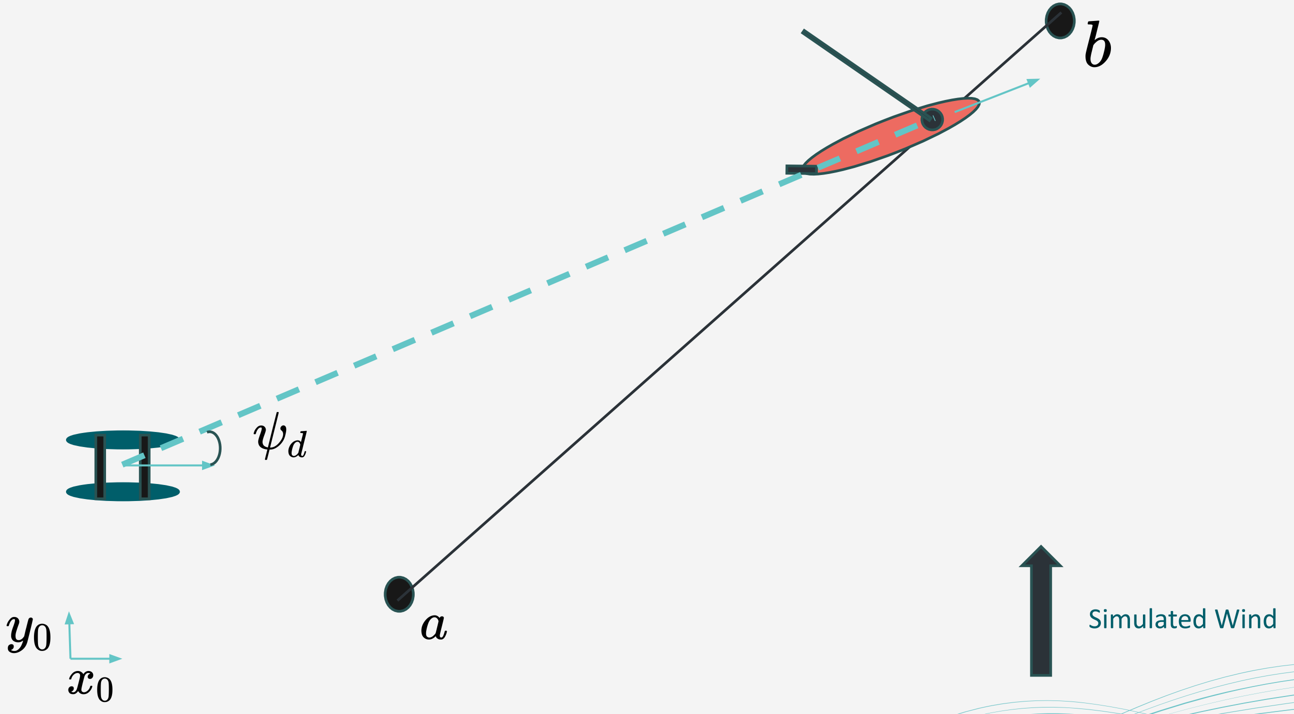
USV Controller
-> 1st phase: Approach

- Conventional fixed-point rallying mission
  - The VSB waits for the USV to catch up
- Line Of Sight Guidance Principle
  - ***Breivik and Fossen**, 2005*

$$\psi_d = \operatorname{atan}\left(\frac{y_{SB} - y_{USV}}{x_{SB} - x_{USV}}\right)$$

$$r = k_r(\psi_d - \psi)$$

$$u = k_u \operatorname{norm}(e_x, e_y)$$



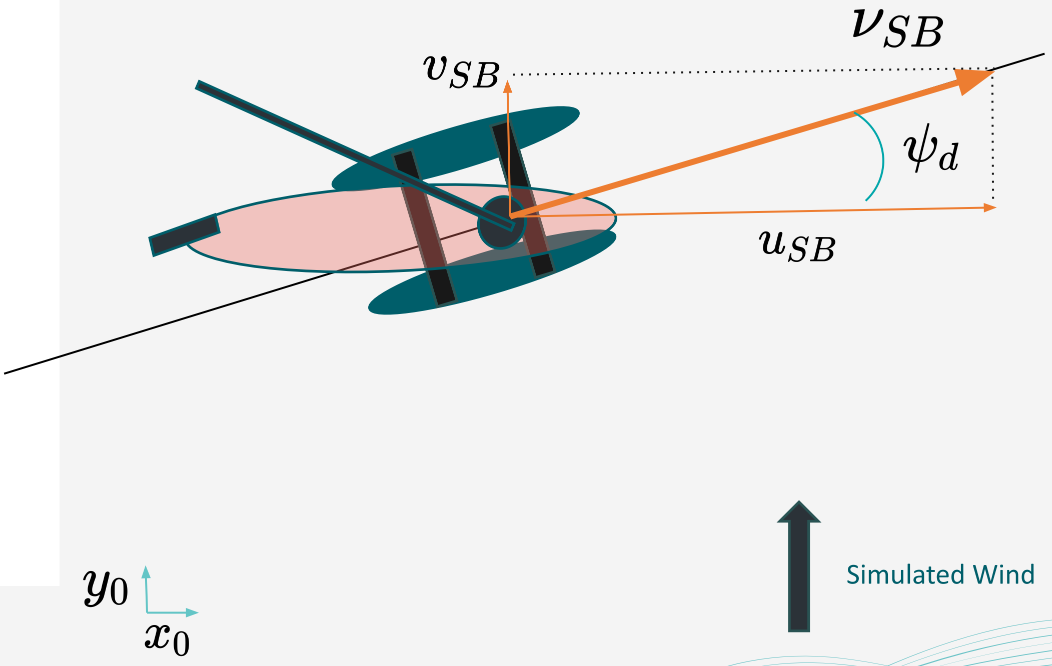
USV Controller
-> 2nd phase: Tracking

- Similar to a conventional trajectory tracking mission
- Drift of the VSB must be taken into account
- The USV must align with the COG angle of the VSB

$$\psi_d = \psi_{SB} + \text{atan}\left(\frac{v_{SB}}{u_{SB}}\right)$$

$$r = r_{SB} + k_r(\psi_d - \psi)$$

$$u = \nu_{SB} + k_u e_{x_B}$$

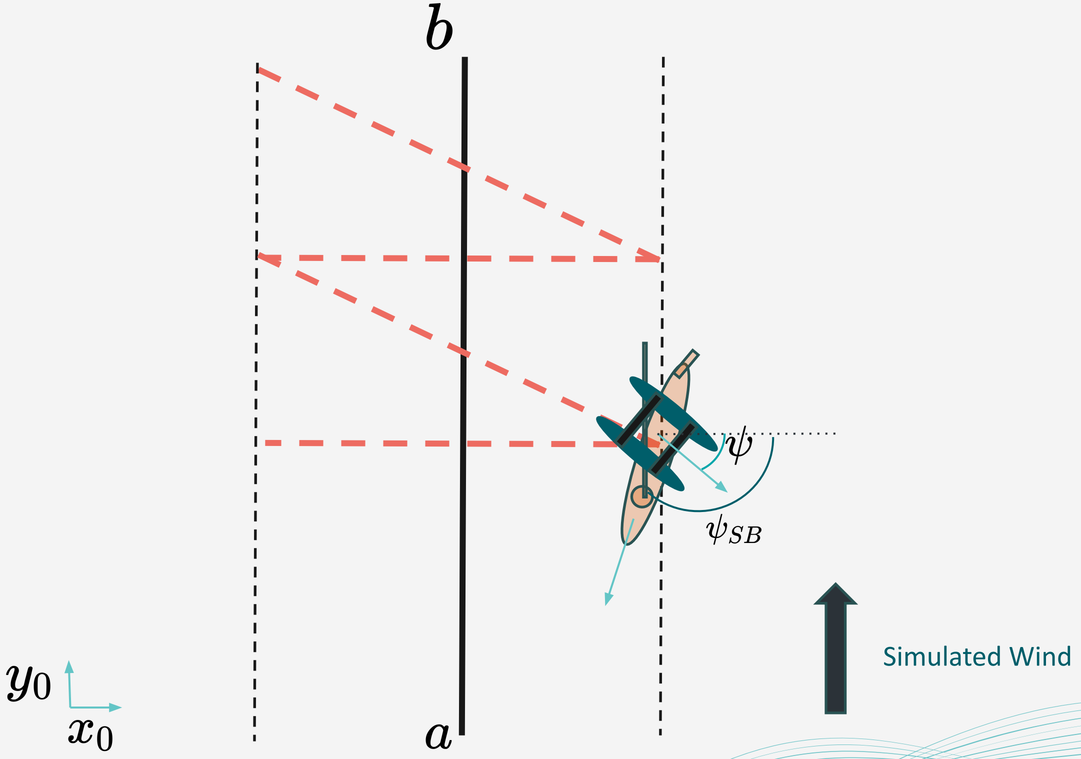


USV Controller
-> 3rd phase: Maneuvers

- Heading angle tracking with zero surge speed
- Conventional P controller with feedforward

$$u = 0$$

$$r = r_{SB} + k_r(\psi_d - \psi)$$

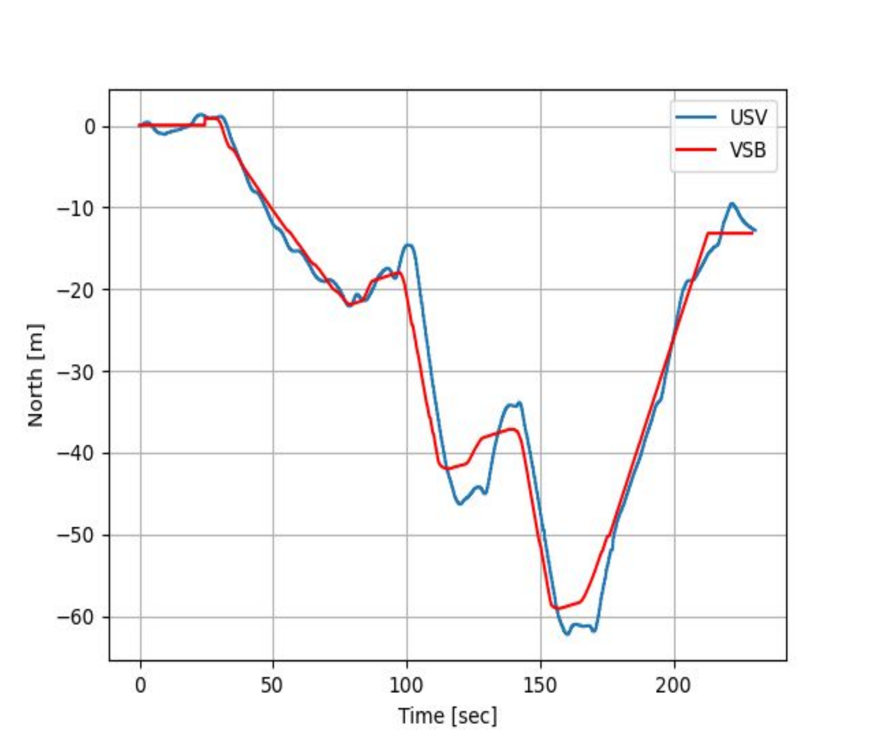


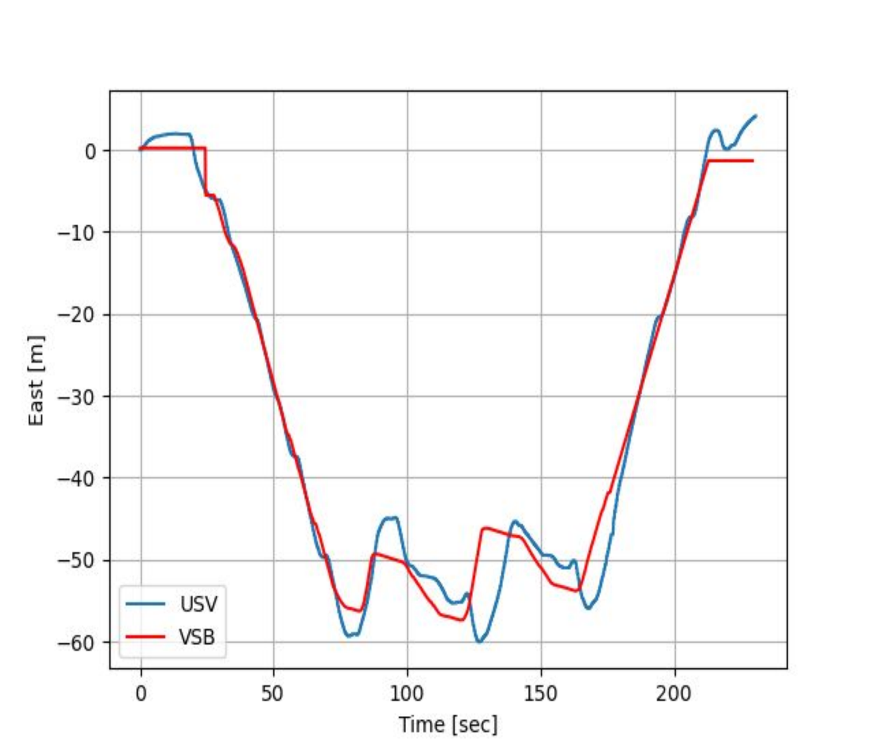
First experiment

The Blueboat tracking the virtual sailboat

Position of the Blueboat (blue) and of the Virtual Sail boat (red)

Experiment Results





Comparison of the position of the Blueboat (blue) and of the virtual sailboat (red) over time

Challenges

Some solutions

∕ Hybrid system

- Synchronization of the physical and virtual systems
- Compatibility of the two vehicles

∕ Limitations of the USV

- Can barely sail forward and turn at the same time
- The Blueboat framework only allows speed control

∕ The USV is very disturbed by the waves, wind and current

→ Upgrade the ROS architecture to ROS2 ?
→ Run more tests to find the limits of the USV and the ideal conditions for the VSB

→ Add of a controlled keel to recreate drifting

→ Upgrade the Blueboat with new ESCs allowing force control

→ Need for advanced guidance and control methods

Perspectives
→ Updates for guidance and control

/ Update to a more robust guidance principle

- Compare different guidance principles

  Degorre et al., ***A Survey on Model-Based Control and Guidance Principles for Autonomous Marine Vehicles***, *2022*

  Fossen, ***A Uniform Semiglobal Exponential Stable Adaptive Line-of-Sight (ALOS) Guidance Law for 3-D Path Following***, *2024*

- Try with the kinematic guidance principle

  L. Degorre , ***Analysis and control of AUVs with reconfigurable vectoring thrust,*** *2023*

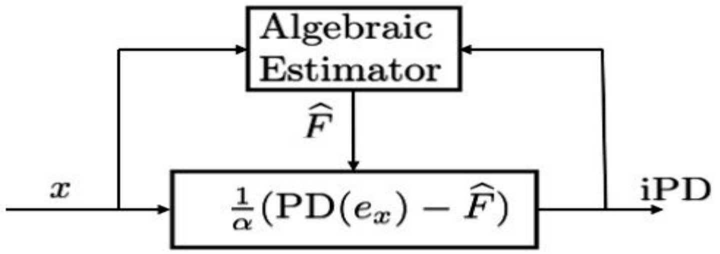
$$\begin{bmatrix} u \\ 0 \\ r \end{bmatrix} = \nu_{SB} + \mathcal{H}J(\nu)\mathrm{PID}(e_x, e_y)$$

/ Study adaptive Model Free Controllers

- The Intelligent Proportional Derivative Controller

  Fliess & Join, ***Model-free control***, *2013*

- Model approximations and external disturbances are estimated and compensated



Perspectives
→ Other future works

- More testing using this framework (gain tuning, testing of new controllers, …)
- Formal stability proof for the control structure of the USV (including delays, hybrid systems,…)
- Extend the method to other systems (AUV tracking a simulated glider for instance)
- Actually test obstacle avoidance strategies


Thank you for your attention
Any question ?
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References

- Singh, M.; Fuenmayor, E.; Hinchy, E.P.; Qiao, Y.; Murray, N.; Devine, D. Digital Twin: Origin to Future. *Appl. Syst. Innov.* 2021, https://doi.org/10.3390/asi4020036
- Lee J.H., Nam Y.S., Kim Y., Liu Y., Lee J., Yang H., "Real-time digital twin for ship operation in waves", *Ocean Engineering*, 2022, https://doi.org/10.1016/j.oceaneng.2022.112867.
- Kinaci O.K., "Ship digital twin architecture for optimizing sailing automation", *Ocean Engineering*, 2023, https://doi.org/10.1016/j.oceaneng.2023.114128.
- He, B., Li, T., and Xiao, J. (March 25, 2021). "Digital Twin-Driven Controller Tuning Method for Dynamics." ASME. *J. Comput. Inf. Sci. Eng.*, 2021 https://doi.org/10.1115/1.4050378
- Armendia, M., Alzaga, A., Peysson, F., Euhus, D. (2019). Twin-Control Approach. Springer, https://doi.org/10.1007/978-3-030-02203-7_2
- M. Breivik and T. I. Fossen, "Principles of Guidance-Based Path Following in 2D and 3D," *Proceedings of the 44th IEEE Conference on Decision and Control*, 2005, doi: 10.1109/CDC.2005.1582226.
- M. Fliess, and C. Join. "Model-free control." *International journal of control* 86.12 (2013)
- T. I. Fossen, A. P. Aguiar, "A uniform semiglobal exponential stable adaptive line-of-sight (ALOS) guidance law for 3-D path following", *Automatica*, 2024,
- L. Degorre, E. Delaleau, O. Chocron, "A Survey on Model-Based Control and Guidance Principles for Autonomous Marine Vehicles". *Journal of Marine Science and Engineering*. 2023 https://doi.org/10.3390/jmse11020430
- L. Degorre. Analysis and control of autonomous underwater vehicles with reconfigurable vectoring thrust. *École Nationale d'Ingénieurs de Brest*, 2023