

Simulation and application of model-based and model-free track controllers for ship manoeuvring in shallow and confined water

MASHCON

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Overview



Overview

Introduction

Controllers in Simulation

- ☐ Interfacing ship manoeuvring models and control for simulation
- ☐ Model-based track controllers
- ☐ Model-free track controllers

Simulations in Shallow and Confined Water

- ☐ Passing the city of Paris on the Seine
- ☐ Ships on the Western Scheldt

Conclusions

Acknowledgements



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Introduction



Research Focus and Levels of Autonomy

► Levels of Autonomy

- Level 1: Steering automation
- Level 2: Partial automation for steering and propulsion control
- Level 3: Conditional automation for collision avoidance
- Level 4: High automation with fallback performance without intervention
- Level 5: Full automation with unconditional performance without intervention

► Current State on Waterways

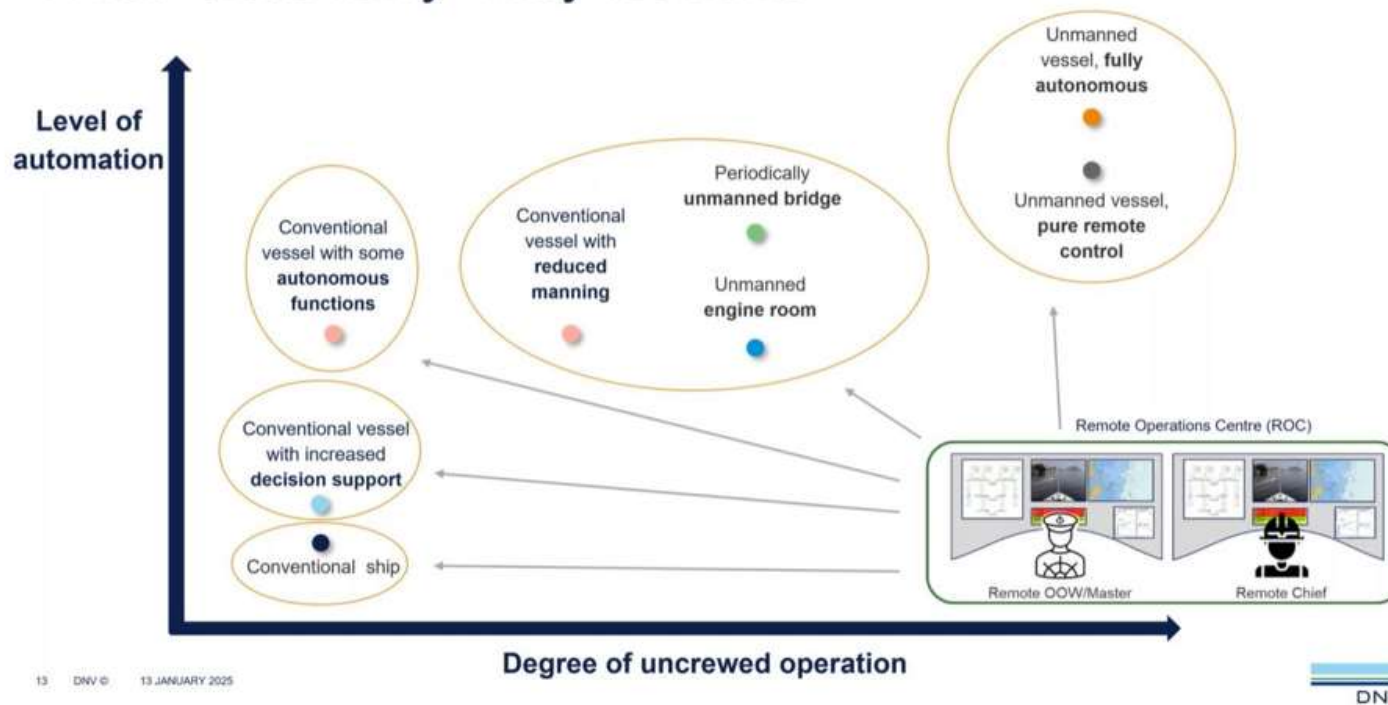
- Not all European waterways are open for remotely controlled ships
- Research institutions and companies are investigating challenges and possibilities

► Path Planning and Path Following

- Focus on reliable path planning and path following by model predictive controllers
- Controllers or autopilots support different levels of autonomy

Automation and Crew Reduction

What “autonomy” may look like



Decision support

Autonomous functions

Remote Operations Centre

Figure 1 What “autonomy” looks like according to DNV (2025) (left) and the key elements in autonomous navigation (right).

Conditions for Automated Ships

- ▶ **Conditions for Ship Operations**

- Shallow and confined waterways with dense traffic
- Interaction with weather, other ships, waterway and constructions

- ▶ **Automated Ship Path Planning**

- Preferred and continuously optimized path
- Consideration of navigational parameters

- ▶ **Path Following Accuracy**

- Use of propulsion and steering systems
- Avoiding paths that cannot be followed

- ▶ **Environmental Constraints in Open Sea versus Restrictions in Shallow and Confined Water**

- ▶ **Predefined Tracks e.g. based on AIS-analysis**

AIS analysis for preferred tracks



Figure 2 Canal Nimy-Blaton-Péronnes at Péruwelz with inbound (greenish colour) and outbound (reddish colour) tracks of inland vessels (15-23/08/2022).

Inland shipping

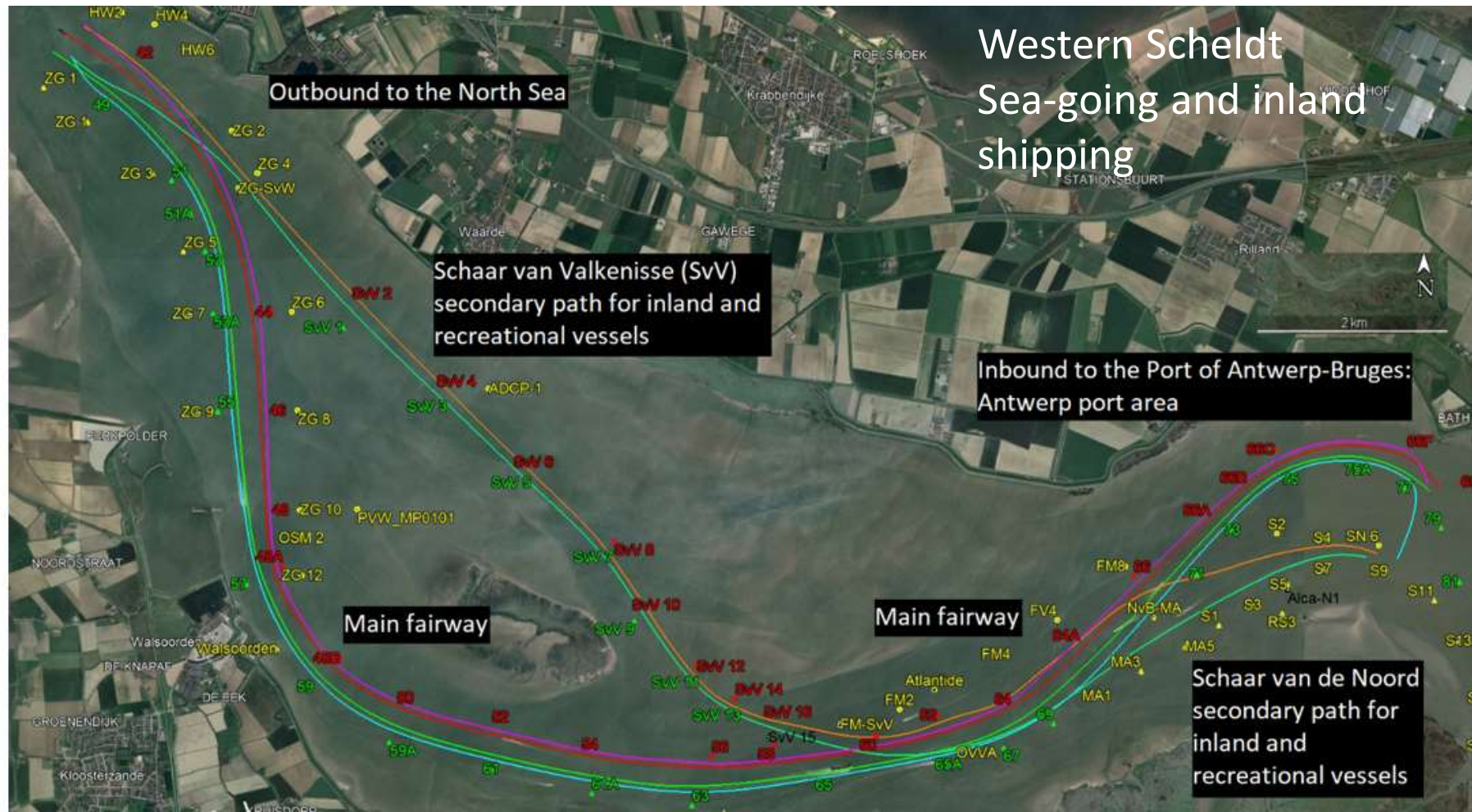


Figure 3 Mean paths of sea-going (green = inbound, red = outbound) and inland (main fairway: blue = inbound, purple = outbound; secondary path: light green = inbound, orange = outbound) vessels on the Western Scheldt main fairway and secondary paths based on AIS-analysis (December 2013).

Data-driven Smart Shipping (DDSHIP)

► Project Overview

- Data-driven Smart Shipping (DDSHIP) initiative
- Collaboration between Flanders Hydraulics, University of Antwerp, and Ghent University

► Objective

- Developing model predictive reinforcement learned (MPRL) path planning and following

► Training and Simulation

- Interfacing simulation software from different institutes
- Creating a digital platform for research and testing

► Target Audience

- Research institutes
- Companies testing technologies like autopilots

Industrial Advisory Board





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Controllers in simulation



Interfacing Ship Manoeuvring Models

- ▶ **Full Mission Bridge Simulators at Flanders Hydraulics**
 - Devoted to ship manoeuvring in shallow and confined water
 - Mathematical models account for various forces
- ▶ **Interfacing for Virtual Test Bed for Autonomous Navigation**
 - Interfacing third-party controllers via new software interfaces
 - Interfaces written in native C++ with .NET wrapper (Interaction with SimSync)

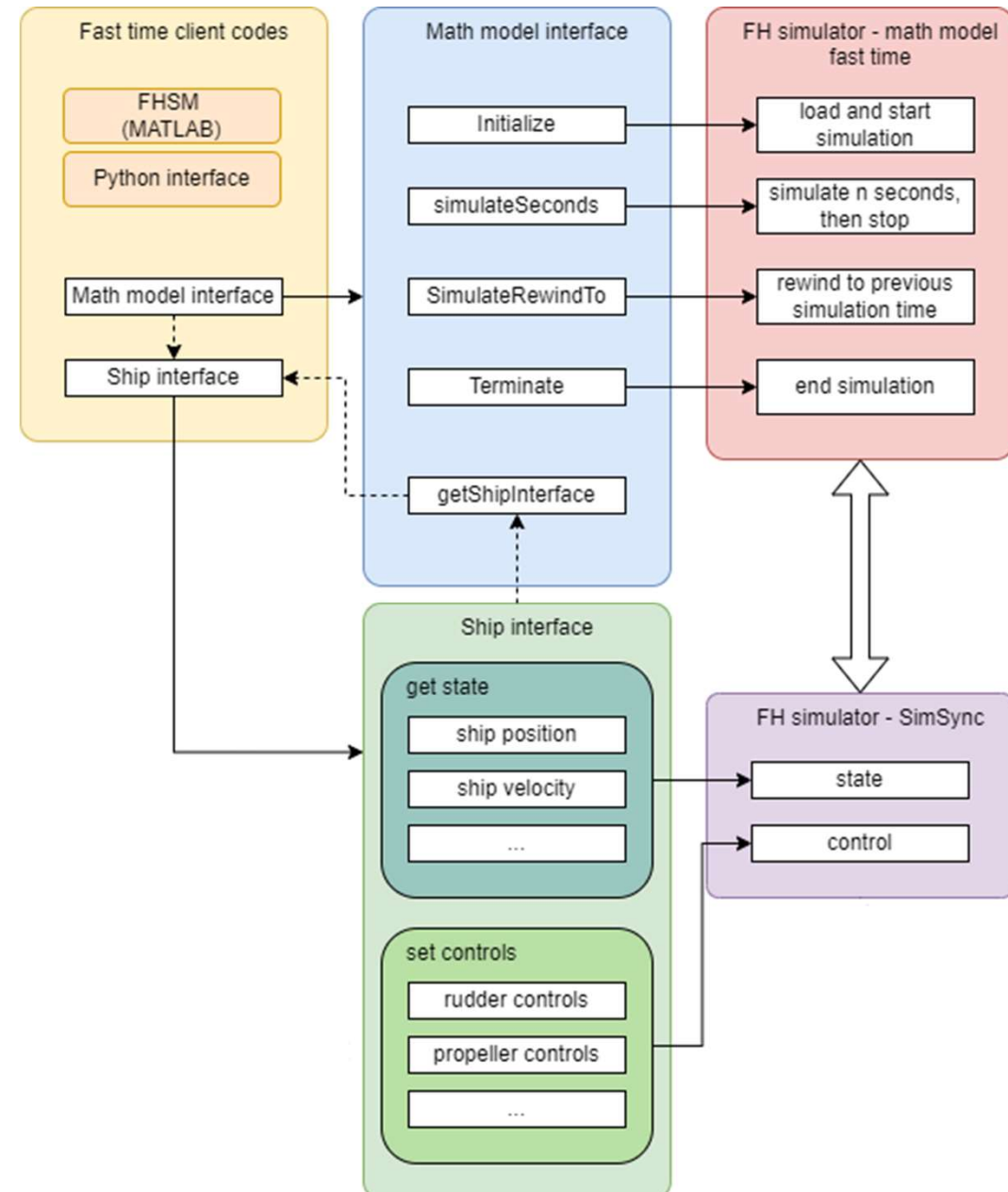
► Control Over Simulation

- Starting, pausing, rewinding, stopping simulations
- Interaction with SimSync communication layer

► Interaction with SimSync

- Read ship state variables (position, velocity in 6DOF)

► Reliable and Practical Interaction



Model-based track controllers

- ▶ Pre-science model based track controller (PMTC) at FH
- ▶ Model Predictive Reinforcement Learning (MPRL) at UAntwerpen
 - Used in various disciplines
 - Mathematical or data-driven models
 - Describe physical behaviour of the system, 1 up to 6 DoF

Cost function

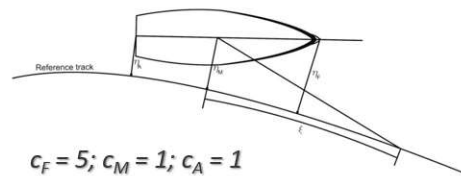


Figure 7.4 Cost function of mathematical pilot model (Vantorre et al., 1997).

(1)

$$C = c_F \eta_F^2 + c_M \eta_M^2 + c_A \eta_A^2$$

PMTC Description and Cost Function

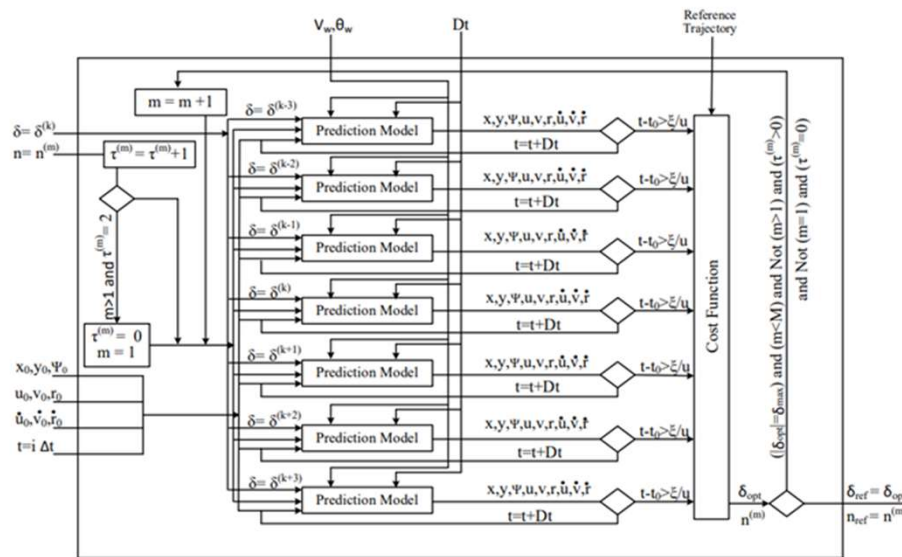


Figure 7.3 Principle of prescience model based track controller in the fast-time simulator (Vantorre et al., 1997).

► Introduction of PMTC

- Developed at Flanders Hydraulics
- First introduced in the 1990s

► Advantages and Drawbacks

- Accurate prediction rate
- Limited availability for all ship types and conditions

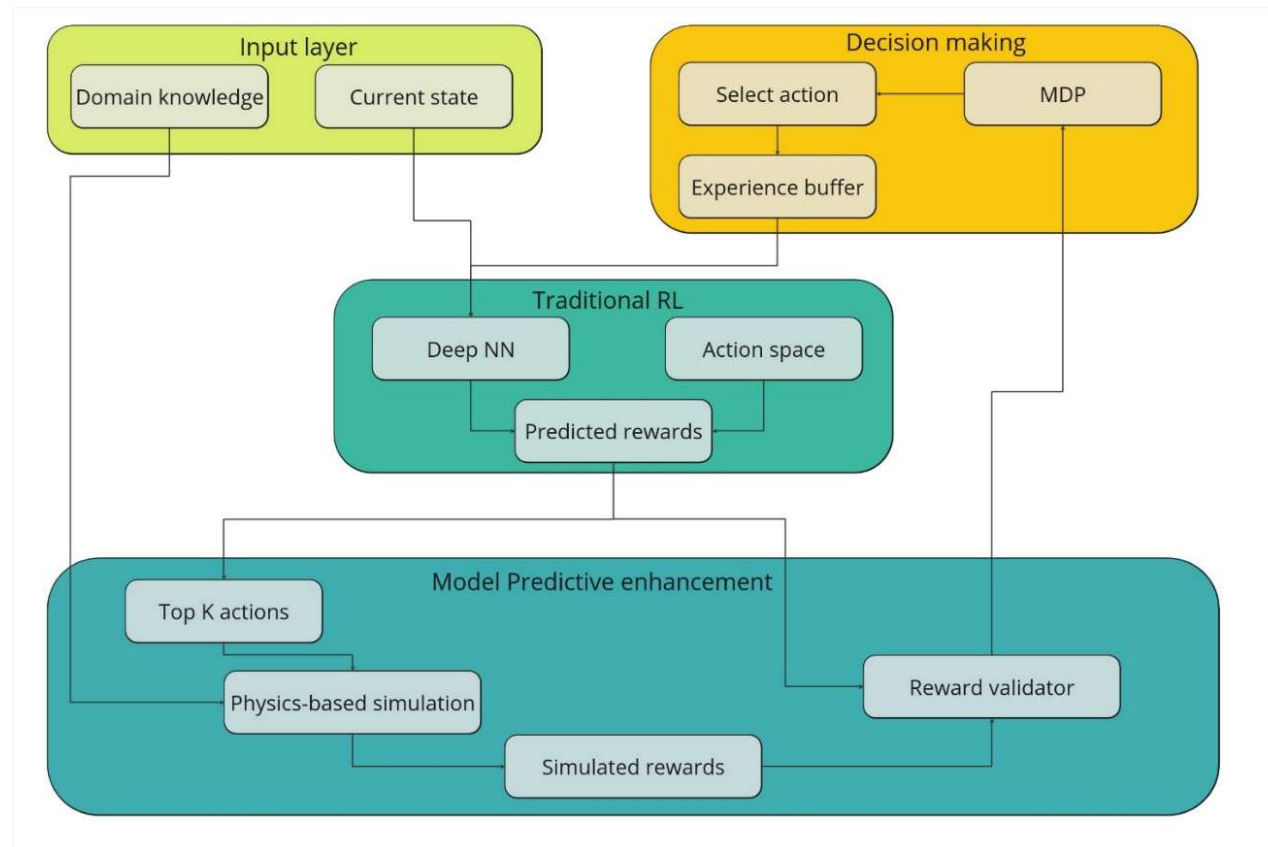
► Principle of PMTC

- Uses high-fidelity mathematical models
- Minimizes deviations from reference track

► Parameters and Tuning

- Propeller rate and rudder angle

Model Predictive Reinforcement Learning (MPRL)



MPRL Description

► Enhancement of RL Algorithms

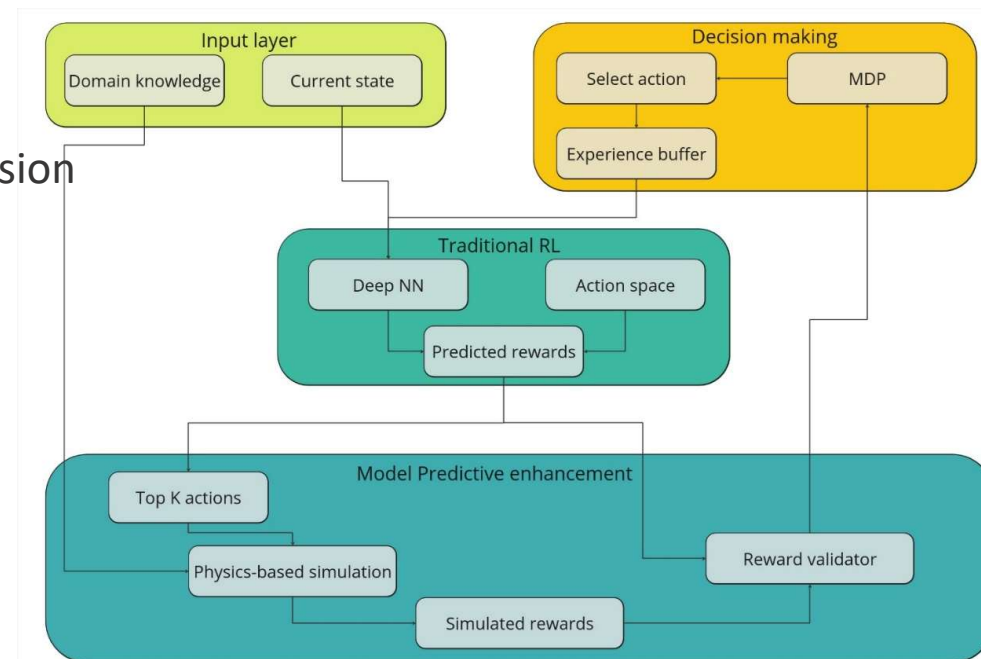
- Incorporates model predictive control
- Uses domain-specific knowledge for collision avoidance
- Handles complex manoeuvring

► Traditional RL Approach

- Deep neural network predicts expected rewards
- Markov Decision Process (MDP) selects actions based on probability distribution

► Proposed Hybrid Approach

- Two-stage process for action selection, subset of actions with highest predicted rewards defined
- Actions simulated to recalculate actual rewards



Model-free track controllers

► Control algorithm

- Use errors comparing actual and desired state for control decisions
- Behavioral constraints are not directly included in the decision process

► PID Controllers

- Evaluates and controls error on actual and desired heading angles
- Proportional, integral and derivative gain

$$\delta = K_P(\psi_d - \psi) + K_I \int_0^t (\psi_d - \psi) d\tau - K_D \dot{\psi}$$

► Fuzzy Controllers

Model-free track controllers

► PID Controllers

$$\delta = K_P(\psi_d - \psi) + K_I \int_{\tau_0}^t (\psi_d - \psi) d\tau - K_D \dot{\psi}$$

► Fuzzy Controllers

→ Components of Fuzzy Controller

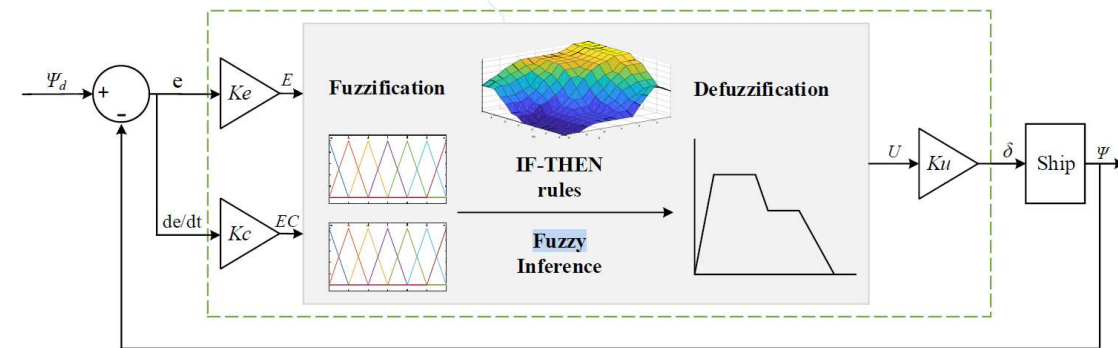
- × Fuzzification
- × Fuzzy rules
- × Fuzzy inference
- × Defuzzification

→ Control Mechanism

- × Heading angle deviation (e)
- × Change in time of deviation (de/dt)
- × Setting of rudder angle (δ)

→ PhD Work Reference

- × Elaborated and tested by Changyuan Chen (2021)





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Simulations in shallow and confined water

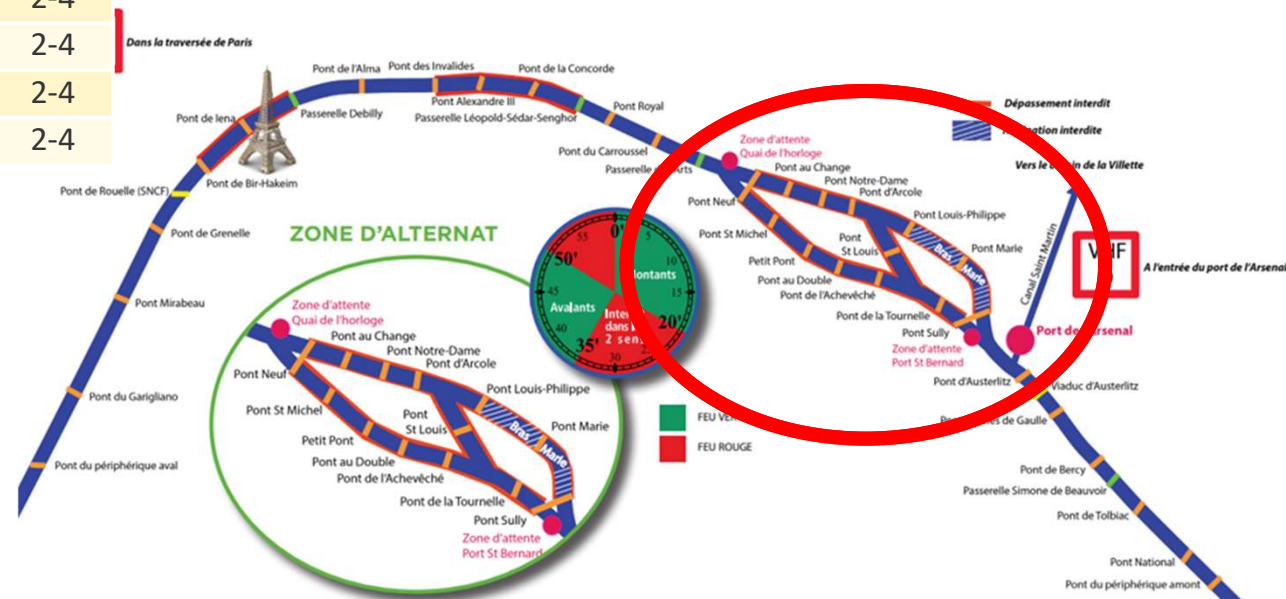


Passing the city of Paris on the Seine

Control/Simulation	Draft	Beam	Water level/current	Wind
Name	[m]	[m]	[cm]	[Bft]
SIM35, human	1.7	10.55	280/280	2-4
SIM36, human	1.7	9.65	280/280	2-4
PMTc0	1.7/2.8	10.55	120/140	2-4
FUZZY0	1.7/2.8	10.55	120/140	2-4
PID0	1.7/2.8	10.55	120/140	2-4
PMTc1	1.7	10.55	280/280	2-4
PMTc2	2.8	10.55	280/280	2-4
PMTc3	1.7	10.55	280/280	2-4
PMTc4	1.7	10.55	280/280	2-4

110 m inland containership

Marc Mansuy et al. (2023)
Elout & Mansuy (2024)



Passing the city of Paris on the Seine

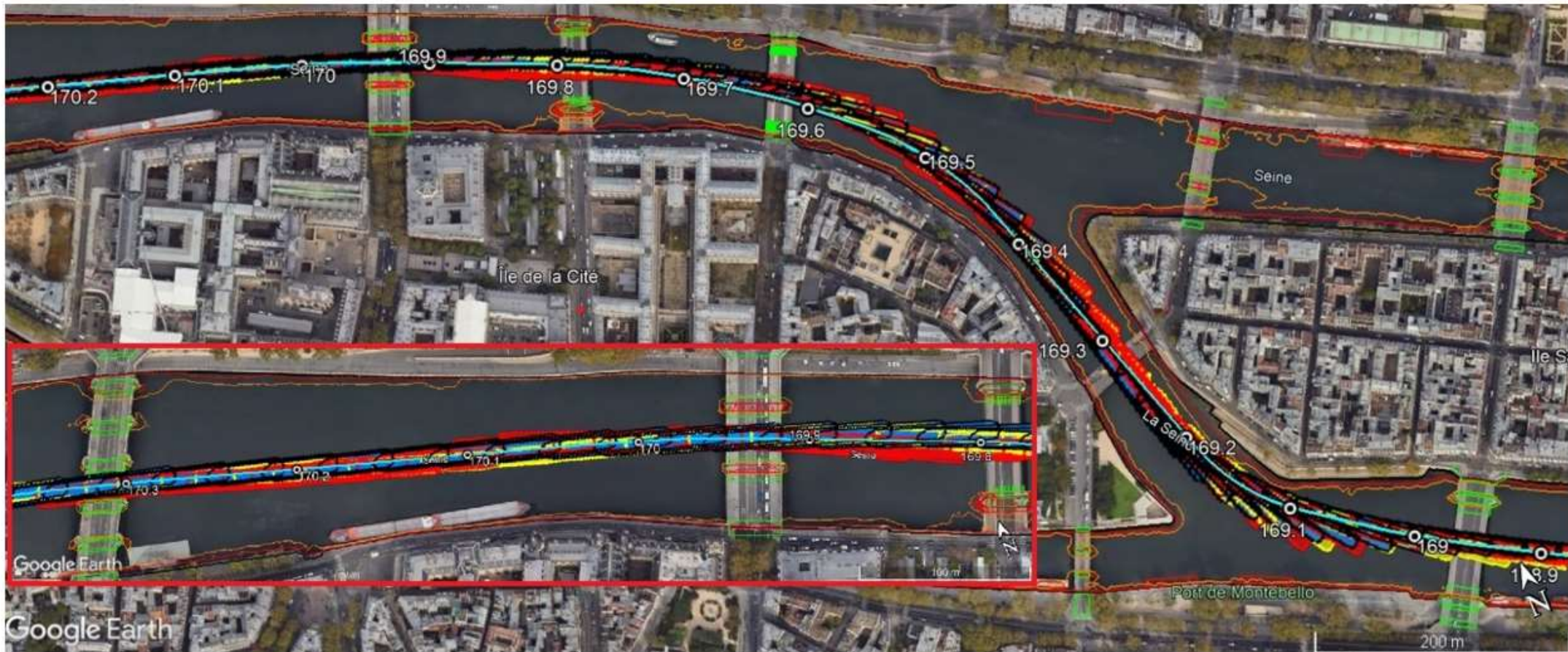


Figure 10 Detail of the zigzag manoeuvre between Ile Saint-Louis and Ile de la Cité with a closer view to the passages of the bridges between km 169.8 and 170.3 (blue with black contour = PMTC0, red = SIM35 and yellow = SIM36 by skipper).

Passing the city of Paris on the Seine

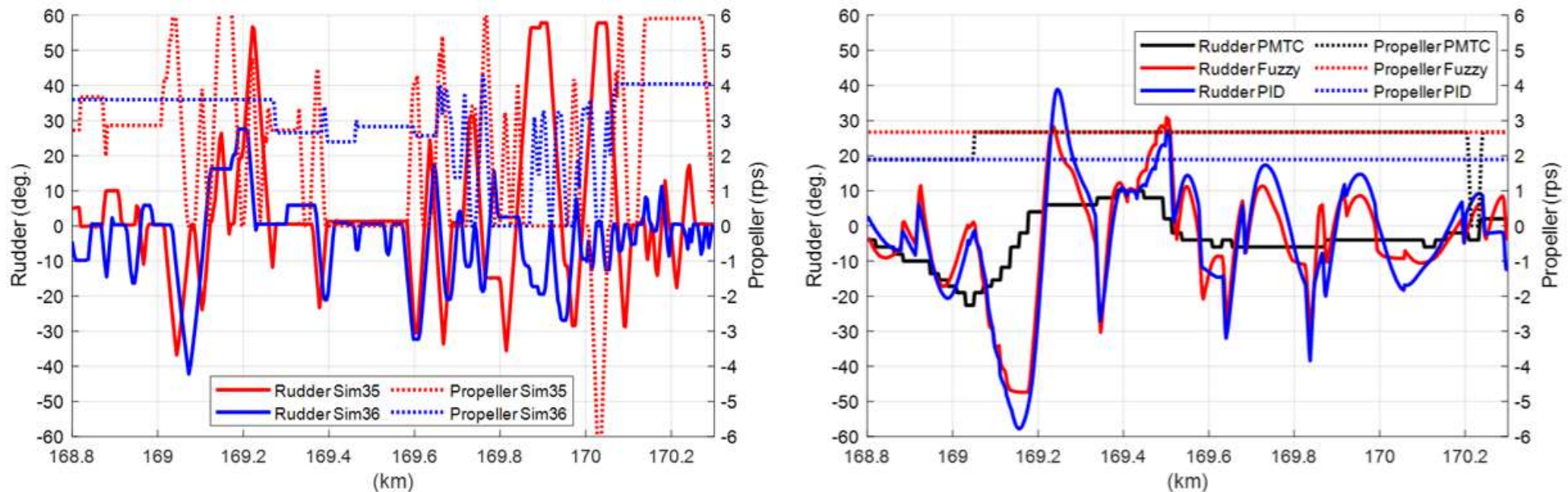


Figure 11 Use of rudder angle (deg) and propeller rate (rpm) for human controlled (SIM35 and SIM36, left) and PMTC0, Fuzzy0 and PID0 simulations within the track between 168.8 and 170.2 km on the Seine in Paris, 110 m vessel at 1.7 m draft.



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human

controller

Passing the city of Paris on the Seine

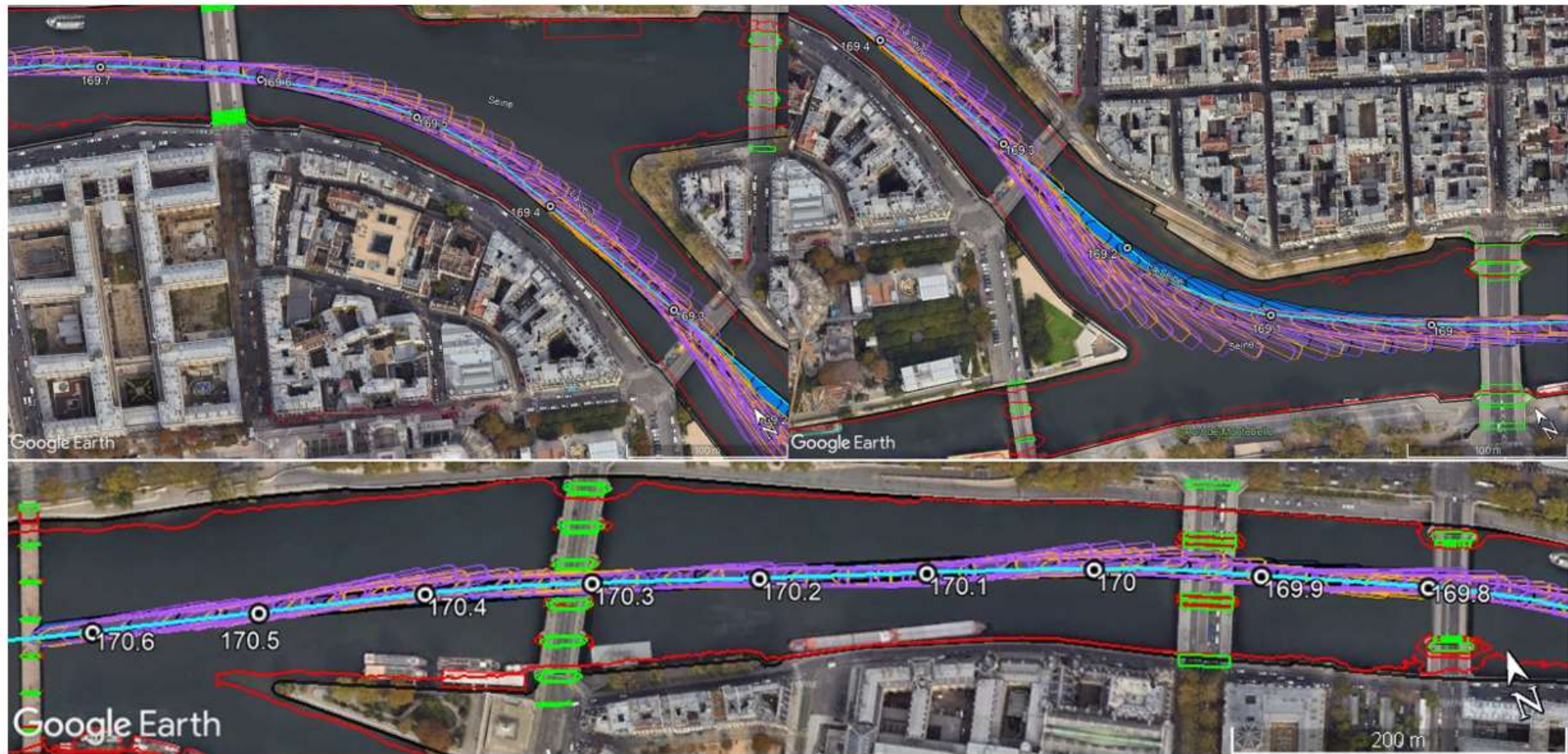


Figure 13 Detailed extractions of the PMTC0 (blue with black contour), FUZZY0 (orange) and PID0 (purple) controlled tracks of the 110 m vessel at 2.8 m draft.

Passing the city of Paris on the Seine

► Performance Indexes

- Mean track error integral (mTEI)
- Maximum track error (MTE)
- Mean rudder integral (mRI)
- Mean rudder total variation (mRTV)
- Mean heading error (mHE)



Control/Simulation	Draft	Water level/current	mTEI	MTE	mRI	mRTV	mHEI
Name	[m]	[cm]	[m]	[m]	[deg]	[deg]	[deg]
SIM35, human	1.7	280/280	2.83	9.04	16.19	3.72	4.79
SIM36, human	1.7	280/280	2.68	7.02	19.78	5.82	4.15
PMTc0	1.7	120/140	2.45	9.20	9.51	0.30	3.98
FUZZY0	1.7	120/140	4.60	18.43	15.81	2.11	5.03
PID0	1.7	120/140	5.65	20.64	18.39	1.59	6.36
PMTc1	1.7	280/280	5.19	14.50	11.44	0.34	6.51
PMTc2	2.8	280/280	3.19	11.11	10.52	0.28	3.82
PMTc3	1.7	280/280	5.05	14.50	11.89	0.36	6.53
PMTc4	1.7	280/280	4.58	13.53	11.57	0.44	5.85

Multi-paradigm simulation methodology

- ▶ **Innovative Methodology for RL Agents**

- Focus on autonomous navigation in shallow and confined waterways
- Addresses challenges of traditional high-fidelity simulators

- ▶ **Hierarchical Approach to Simulation Fidelity**

- Modular framework for integrating different simulators and AI solutions
- Starts with low-fidelity simulations and incorporates higher-fidelity models

- ▶ **Two-stage Process Demonstration**

- Initial training in a computationally efficient 2D environment
- Progression to Flanders Hydraulics simulator

- ▶ **Future Work**

- Extending training methodology to additional paradigms and simulators
- Validating the effectiveness of the modular framework

Ships on the Western Scheldt

	mTEI	MTE	mHEI
Environment	[m]	[m]	[deg]
2D simulator	0.57	3.95	3.44
FH simulator – no wind and no current	21.38	54.24	6.88
FH simulator – wind and no current	24.91	60.66	8.59
FH simulator – wind and current	46.60	164.28	10.31

$$\frac{du}{dt} = k_t \cdot T + X_u \cdot u$$

$$\frac{dv}{dt} = k_v \cdot \sin(\delta) + Y_v \cdot v$$

$$\frac{dr}{dt} = k_r \cdot \delta + N_r \cdot \frac{v}{L}$$

Blue preferred track
Green no wind/current
Yellow wind/no current
Red wind/current





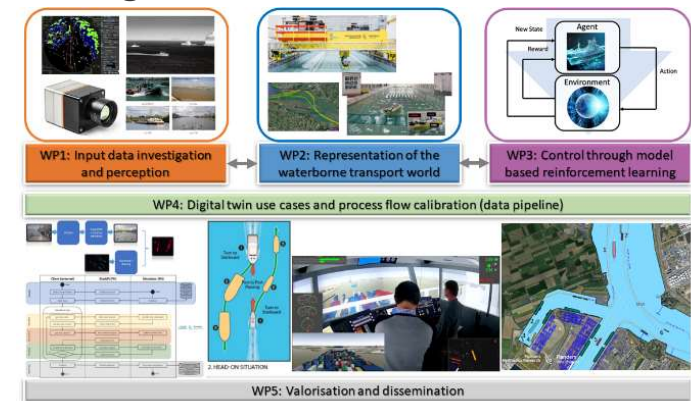
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Conclusions Data-driven smart shipping



Conclusions

- ▶ **Integration of Knowledge from Different Domains**
 - Researchers from various backgrounds collaborate through DDSHIP project
 - Combines situational awareness, model predictive control, and AI trained agents
- ▶ **Model-Based and Model-Free Track Controllers**
 - PMTC uses advanced mathematical models for predictions
 - Fuzzy and PID controllers reduce deviation and heading errors
- ▶ **Model Predictive Reinforcement Learning Controllers**
 - Enriched by mathematical models on physics
 - Focus on path planning and path following
- ▶ **Comparison of Controllers**
 - PMTC, Fuzzy, and PID controllers tested on river Seine and confined river passages, compared to human executed simulations
- ▶ **Future Exploration with project deadline end of 2026**





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Q&A

