Autonomous Ship Control in Shallow and Confined Water

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SUMMARY

The paper describes the definition and usage of autonomous ship control systems in shallow and confined water. The application of such control system is shown in a case study : a systematic analysis of ship transits in the approach channel to the Port of Antwerp (Western Scheldt) .The control algorithm not only is capable of correctly navigating the ship through the fairway, it also delivers insight in rudder and propeller usage in function of the tidal conditions. Such control systems are validated based on model tests carried out in towing tanks. Flanders Hydraulics Research (FHR) has recently inaugurated their second towing tank, the Towing Tank for Manoeuvres in Shallow Water. One of the functionalities of this facility is the role it can play as test basin for autonomous shipping. Next to the further validation and expansion of existing control scenarios, it will be used to model interaction events between multiple ships. A numerical effort to model interaction events is presented, which will be validated in the model test basin.

NOMENCLATURE

ADRC	Active Disturbance Rejection Control
ATFMS	Angle-Guidance Tuned Fast Marching Square
IMO	International Maritime Association
FHR	Flanders Hydraulics Research
FML	Flanders Maritime Laboratory
FMM	Fast Marching Method
MASS	Maritime Autonomous Surface Ships
PMTC	Prescience Model Track Control
ROS	Robot Operating System
UKC	Under Keel Clearance
ULCS	Ultra Large Container Ship

1. INTRODUCTION

Autonomous technology is the next big development in the shipping industry. IMO [1] is setting up a framework to regulate such MASS (Maritime Autonomous Surface Ships). The transition from manned to autonomous, potentially unmanned, shipping comes with many technological and legislative challenges. A major technological requirement involves the development of ship control systems, which are able to guide the ship when navigating and interacting with other waterway users. A basic control system can fulfil such task when sailing in open oceans, where navigational areas are large. In shallow and confined waterways, the ship's response under rudder and propeller action will vary based on the section's characteristics (UKC, blockage) and the ship will need to interact frequently with other waterway users. Such conditions are typically encountered on the end points of the route (access channels, ports), but can also be present in transit (Panama Canal, Suez Canal, Straight of Malacca,…). Advanced control systems are required to navigate in these shallow and confined areas.

This paper presents the different parts of an autonomous navigation system (chapter 2), with at the heart of it the ship control system. Chapter 3 describes the validation of control systems through towing tank tests. Chapter 4 presents a case study for the approach to the Port of Antwerp, where an autopilot is used to examine the effect of tidal conditions on rudder and propeller usage. In chapter 5, the complexity of interactions between multiple ships is elaborated on. A numerical simulation example is given as well as insight in FHR's new testing facility. Chapter 6 gives a conclusion and look ahead.

2. AUTONOMOUS SHIP CONTROL SYSTEMS

2.1 GENERAL STRUCTURE

In order for a ship to navigate autonomously, a number of subsystems need to be developed (figure 1). The ship should plan her own path (path planning module). A guidance system ensures that the ship follows the planned path to the best of her ability. To do so, the ship should be able to communicate with her environment through sensory equipment (navigation system). A control system is needed to translate the feedback from the guidance systems to rudder and propeller actions, which eventually steer the ship.

2.2 PATH PLANNING ALGORITHM

A performant path planning algorithm is the essential starting point of the loop. Several path planning modules exist. The FMM (Fast Marching Method) was used as basis and further evolved into an ATFMS (Angle-Guidance Tuned Fast Marching Square). This module is capable of planning a path in an environment with many constraints, avoiding obstacles and considering a safety distance with respect to the obstacle.

2.3 GUIDANCE SYSTEM

As was the case for the path planning system, multiple ship guidance systems have been developed. Most common applications look ahead to coming waypoints (resulting from path planning). A LOS (Line Of Sight) system is a popular approach and is used here.

2.4 CONTROL ALGORITHM

The control algorithm, where the system provides input for propeller and rudder, is of most interest to FHR, as it is directly linked to the study domain of hydrodynamics. This system should be capable of giving appropriate commands to rudder and propeller to accurately control the ship. The list of control algorithms is long, they all however rely on appropriate tuning of a certain set of control parameters. In this paper, three control systems are discussed. The (adaptive) PID system is the most well-known control system, where rudder action is a function of a proportional (P), integral (I) and derivative gain (D) of the heading offset. A Fuzzy type controller translates heading offsets into normalised error coefficients, which are sent through an 'IF-THEN' rule system and eventually 'defuzzied' to obtain a rudder action. An ADRC (Active Disturbance Rejection Control) type controller employs a tracking differentiator to track the reference signal and its differential, with the function of noise reduction. An extended state observer is used to estimate the environmental disturbance and unmodelled systematic uncertainty, greatly increasing the robustness of the controller as it then does not need precise description of the system.

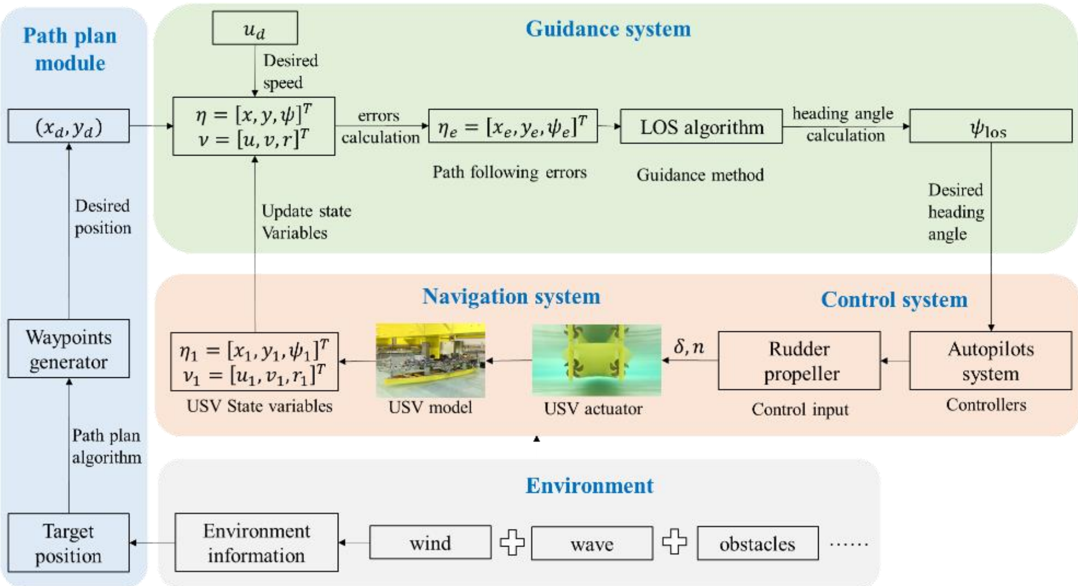

Figure 1 : Components autonomous control loop MASS. [2, figure 1.7]

3. TOWING TANK TEST VALIDATION OF CONTROL SYSTEMS

The complexity of the autonomous control system(s), as well as the consequences of a malfunction or error, makes it difficult to test the algorithms in real life situations. The most interesting validation cases (ship interaction, sailing in shallow and narrow channels) are also not realistic to perform on full scale. Many real life applications are either situated in unrestricted waters (e.g. Mayflower Autonomous Ship[1]) or use scale models in existing waterways [3]. A towing tank facility delivers a controlled environment, offering the possibility to tune and test control algorithms in the most challenging conditions, with systematic parameter variations. A numerical validation case is discussed in chapter 4.

[1] https://mas400.com/, accessed 2022/02/28

3.1 TOWING TANK FOR MANOEUVRES IN CONFINED WATER

The Towing Tank for Manoeuvres in Confined Water (FHR, co-operation with Ghent University) has been in operation for 30 years. The towing tank [4] is capable of performing unsupervised tests 24/7. This unique asset not only allows to generate mathematical models [5], including tuning the ship control algorithms presented in section 2.4, it can be used to validate the performance of such models, through the execution of free running tests [6].

3.2 VALIDATION EXPERIMENT RESULT

Figures 2 and 3 give an example of a validation run for a ship control system which is capable of avoiding obstacles. Within the Towing Tank, four virtual obstacles are defined. The ATFMS algorithm determines the most efficient trajectory, with as boundary condition keeping the risk level of colliding with an obstacle acceptable. Based on the LOS-guidance system, the PID controller provides input to rudder and propeller in order to follow the desired path, delivered by AFTMS, as closely as possible. By using virtual obstacles, the system is allowed to fail and hit an obstacle, which delivers valuable insight in the robustness of the proposed control systems. The results in figures 2 and 3 shows that the control systems respond appropriately when confronted with shallow water conditions, as well as obstacles.

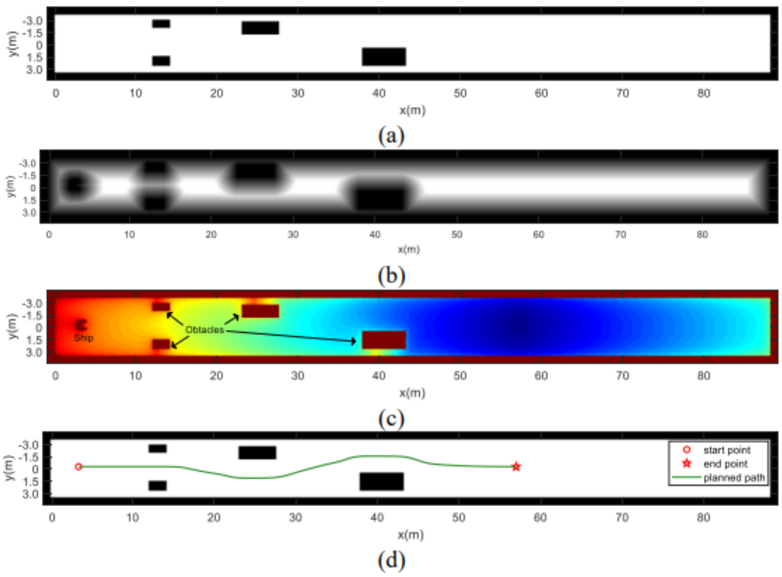

Figure 2 : ATFMS path planning method, four virtual obstacles built into towing tank, (a) grid map, (b) velocity map, (c) time map, (d) planned path. [2, figure 4.12]

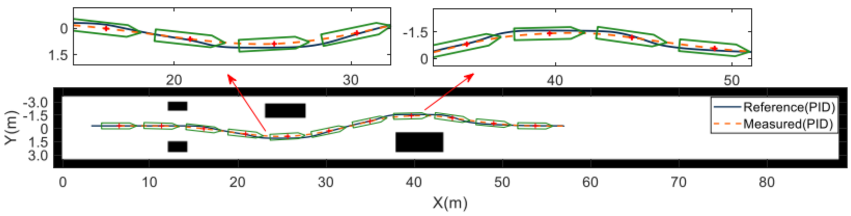

Figure 3 : Comparison reference path (ATFMS path) and measured track (PID control). [2, figure 6.45]

4. CASE STUDY – WESTERN SCHELDT APPROACH PORT OF ANTWERP [7]

4.1 WESTERN SCHEDLT APPROACH CHANNEL

The Port of Antwerp is one of the major European ports. All (seagoing) ships which call the port need to travel through the Western Scheldt access channel (figure 4). This 80 km long fairway is considered shallow (h/T < 4, ITTC), and in some stretches, ships will sail at a minimum allowed UKC of 12.5% [8]. This shallowness, in combination with the tidal influence (water level), makes that ships with drafts above 13.1 m are limited in their allowed tidal window. Deploying autonomous technologies in this stretch is challenging, it however serves as a great test case for general deployment of control systems, as it features both complex turning manoeuvres, as well as may ship-ship interactions. In this case study, the developed autonomous algorithms (path planning, guidance, control) are used to simulate the journey of a ULCS, under varying tidal conditions.

Figure 4 : Approach channel (Western Scheldt) to Port of Antwerp, detail 'Bocht van Bath' section.

4.2 SHIP MANOEUVRING AND CONTROL MODEL

The mathematical ship manoeuvring model used in the simulator takes into account shallow water dynamics [9] and bank effects [10] among many other hydrodynamic effects. The simulator has been validated during real-time simulation runs with experienced pilots. A ship control algorithm makes it possible to perform fast-time simulations, without human interaction (by captains, pilots). Since 1997, FHR implemented an algorithm to simulate pilot decision making, denoted as PMTC (Prescience Model Track Control [11]). The development of control systems for autonomous shipping, can also be used to further optimise track controllers for fast-time simulations. The Fuzzy controller was therefore introduced in the simulator code, not only to improve ship control, also to drastically reduce calculation times.

4.3 SIMULATED RUDDER ACTIVITY

Figure 5 shows the tidal and location dependent rudder action required to follow the reference path, for a ULCS (Ultra Large Container Ship). These results reveal the critical locations and conditions for inbound and outbound ULCS on the Western Scheldt. The methodology can be applied to investigate the impact of environmental (bottom variations, wind, etc.) and operational (ship speed, eccentricity) conditions on the safety of navigation. The zone around position km 70 (dashed rectangle) is the Bocht van Bath section, which was already indicated in figure 4.

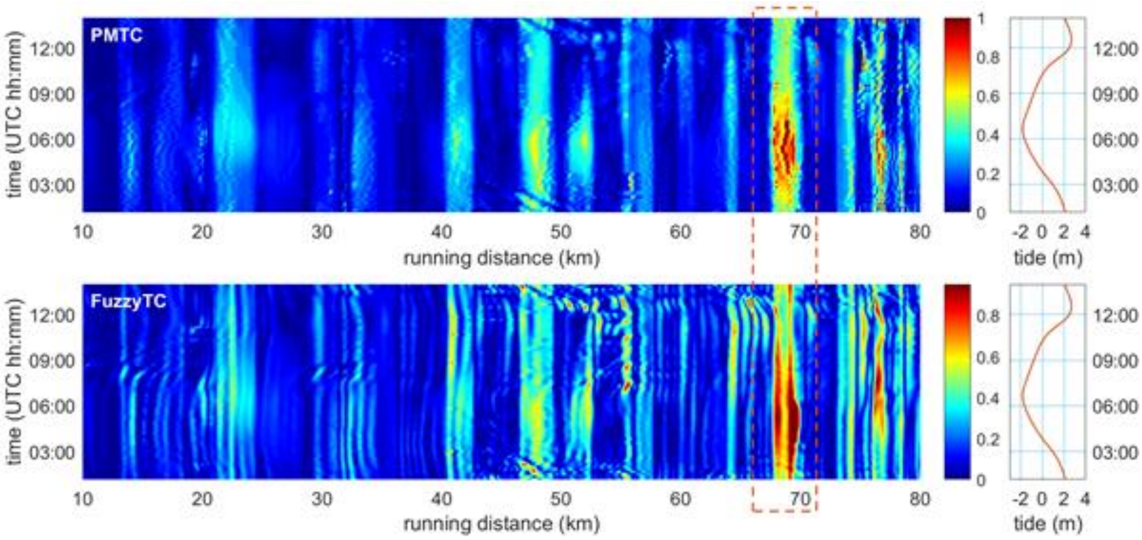

Figure 5 : Comparison PMTC and FuzzyTC for Western Scheldt approach to Port of Antwerp, based on 78 fast-time simulation runs for the entire 70 km path and full tidal cycle.
Red colour represent large rudder angles, the blue colour represents small rudder angles. [7, figure 30]

5. HYDRODYNAMIC INTERACTION BETWEEN MULTIPLE AUTONOMOUS SHIPS

It is undeniable that appropriate ship control algorithms need to be in place, which take into account local shallow and confined conditions, it is however crucial that said ship can interact with other waterway users. The Towing Tank for Manoeuvres in Shallow Water (FHR, co-operation with Ghent University) [12] at Flanders Maritime Laboratory (FML) forms the ideal test basin to validate such control applications. As was the case for a singular controlled ship, numerical simulation models will form an important complementary aspect of this research effort.

5.1 TOWING TANK FOR MANOEUVRES IN SHALLOW WATER AS AUTONOMOUS TEST BASIN

An autonomous test basin needs to have sufficient dimensions to allow several ships to interact with each other throughout the basin. The basin environment allows setting predetermined water levels, as well as adding banks and quay walls to represent confined conditions in ports and access channels. Figure 5 gives an impression of the well-known benchmark KVLCC2 ship at scale 1:75 sailing through the basin. The ship is controlled via a ROS system, with GPS, gyroscope and camera's position identification, as well as rudder and propeller control and feedback. The ROS environment, developed by Kapernikov, allows to easily configure the system as well as to communicate between different ships. The ROS module will also be able to communicate with the towing carriage, which is planned to be in service by the end of 2022, further increasing the flexibility of the system.

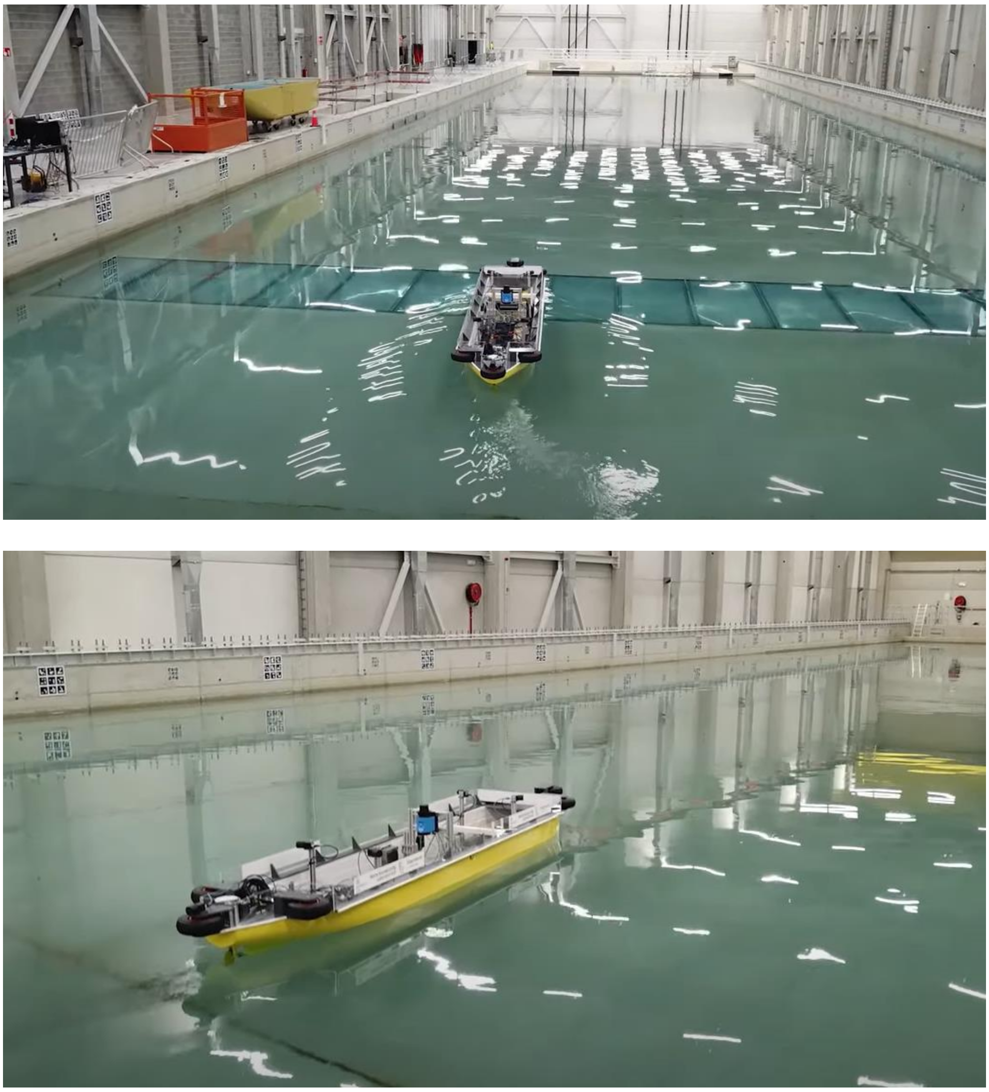

Figure 5 : Autonomous controlled (ROS) KVLCC2 ship, scale 1:75, in the Towing Tank for Manoeuvres in Shallow Water (FML, Ostend).

5.2 RESULT FREE RUNNING TEST

Figure 6 shows the measured time traces for the manoeuvre shown in figure 5. It is a standard 20/20 zigzag manoeuvre [6], which is executed after the ship is accelerated on a straight line based on PID course control. A crash stop manoeuvre is used to end the experiment when the ship is positioned the end of the tank. Although the manoeuvre itself is part of general accepted practice, its execution in combination with a controlled acceleration and deceleration, along with ROS position measurement, shows the potential of the system to perform any autonomously controlled manoeuvre. This set-up will be used to extend the research shown in figure 2 and 3, with more (dynamic) obstacles. It will allow to validate interaction events between two (or more) sailing ships, which are momentarily being modelled numerically (e.g. crossing of ships following the COLREGs). Another numerical application is shown in the next section for ship meetings on the Western Scheldt approach to Port of Antwerp.

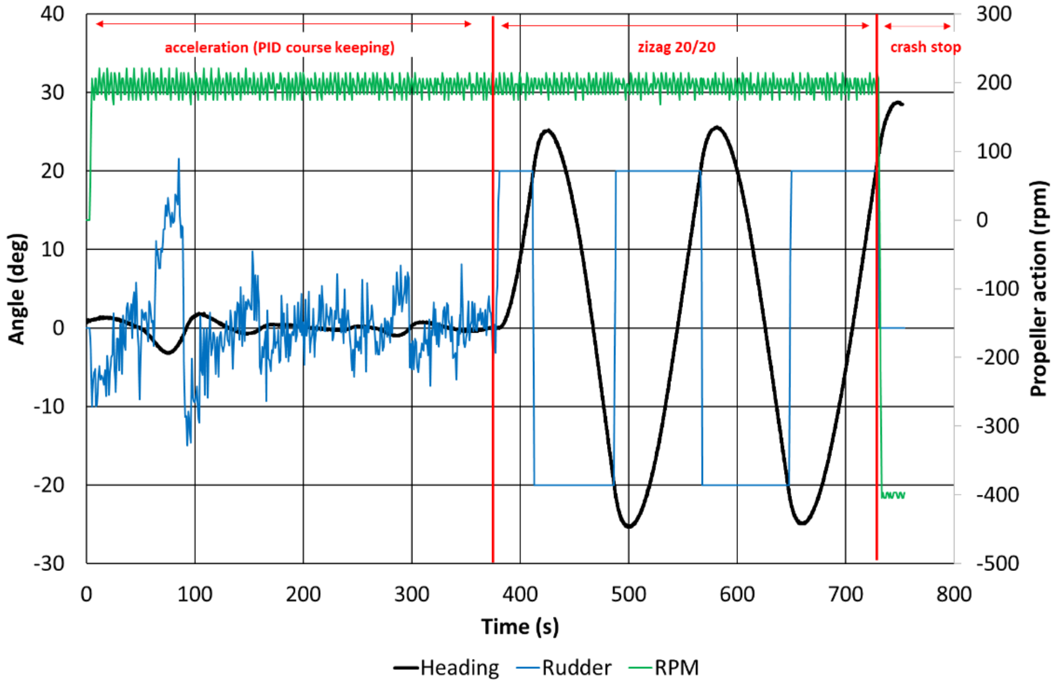

Figure 6 : Autonomous controlled manoeuvre, measured heading, rudder angle and propeller rpm in function of time; Manoeuvre consists of acceleration (PID controlled), 20/20 zigzag and crash stop.

5.3 FAST-TIME SIMULATION

FHR's fast-time simulator allows coupling the in-house mathematical ship manoeuvring model with autonomous controllers, as was shown in section 4. As programming, connecting and implementing such algorithms takes considerable time, a more simple, from perspective of the mathematical model prediction capabilities, Fossen-type [13] fast-time simulator has been developed. By using this straightforward model, a large variety of control algorithms and situations can be simulated. Figure 7 shows a section of the Western Scheldt (detail of figure 4), where the ship sails from right to left in all subfigures. The ship, the Fossen Tanker, follows a predefined path (yellow), which is generated based on waypoints selected on the map. The resulting track of the ship, under the guidance (LOS) and control (ADRC), is indicated in red. When the ship however meets another waterway user (yellow dashed circle), she is able to modify her local path, in order to safely meet with the other ship. The bottom images show how the planned path has been modified (yellow), as well as the resulting track of the ship (red).

Figure 7 : Fossen Tanker navigating through Western Scheldt. Planned path indicated in yellow, followed track indicated in red. From top left to bottom right, four clips from the simulation in chronological order, where the Fossen Tanker encounters an anchored ship and changes her path accordingly.

6. CONCLUSIONS AND FUTURE WORK

Control systems for autonomous shipping are evolving fast. FHR and Ghent University have developed and validated several algorithms which are capable of controlling system in shallow and confined conditions. They also use the control algorithms for systematic fast-time simulation studies, which support accessibility studies, amongst other for Port of Antwerp. The establishment of the Towing Tank for Manoeuvres in Shallow Water, including the deployment of the ROS based free-running system, will allow FHR to further continue their research in state-of-the-art control algorithms. The next focus will be on avoiding (dynamic) obstacles and interaction between multiple ships. The controlled basin environment allows to test the most challenging conditions, where the system can fail in order to developed a risk assessment framework.

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8. AUTHOR BIOGRAPHY

Thibaut Van Zwijnsvoorde, PhD, civil engineer, is a nautical researcher at Flanders Hydraulics Research. He is part of the team developing the Towing Tank for Manoeuvres in Shallow Water. He has experience in probabilistic assessment of estuary vessels, as well as modelling the behaviour of moored ships at berths.

Guillaume Delefortrie, PhD, naval architect, is expert nautical researcher at Flanders Hydraulics Research and visiting professor at Ghent University. He is in charge of the research in the Towing Tank for Manoeuvres in Confined Water and the development of mathematical models based on model tests. He has been a member of the 27th to 29th ITTC Manoeuvring Committees.

Evert Lataire, PhD, naval architect, is professor and head of Maritime Technology division at Ghent University. His research focuses on the behaviour of ships in shallow and confined waters and is often based on model tests. In recent years his division diversified to other floating devices subject to waves and current (aquaculture, floating PV-panels in an offshore environment).

Hongwei He, PhD student, naval architect, is a nautical researcher at Ghent University. His research interest includes automatic systems for ship motion control and modelling the behaviour of manoeuvring ships in calm water or shallow water based on system identification methods.