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Design and Build of an Autonomous Catamaran Urban Cargo Vessel

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Abstract. This study introduces a novel test bed, named the *Maverick*, which aims to advance the field of autonomous inland waterborne freight transportation and facilitate its eventual implementation. More specifically, the *Maverick* focuses on operating in small waterways within urban areas, aligning its application scenario with the European project AVATAR. The hull form of the *Maverick* was selected to be a catamaran, as it offers several advantages, including a large open deck area, high transverse stability, and excellent maneuverability at low speeds. The *Maverick* is equipped with two 360-degrees-steerable azimuth thrusters, one at the bow and one at the stern. This configuration makes the *Maverick* over-actuated, and offers more advanced motion control possibilities compared to conventional rudder-propeller actuated vessels. The *Maverick* is composed out of modular building blocks combined with a flexible interface, which enables it to accommodate diverse control terminals for future developments. Furthermore, to illustrate the feasibility of the *Maverick* within an urban context, this study also includes results of several trail tests. The interactive communication framework that was successfully employed in the autonomous sailing experiment is introduced. The *Maverick* offers a versatile platform for testing and developing a wide range of technologies in situation awareness, autonomous sailing, smart waterway logistics, and other interconnected domains. Therefore, this innovative research vessel can pave the way for the development of a new freight transport mode within European urban areas, contributing valuable experiences to the field.

1. Introduction

According to the European Commission[1], freight transport is projected to increase over 58% by 2050 or 1.2% each year, necessitating improvements in the capacity of the transportation system. Most freight is currently carried by road, which incurs high and escalating external costs, such as accidents, air pollution, climate change, noise and congestion. For instance, the cost of road congestion in European Union member states already accounts for 1 to 2% of Gross Domestic Product (GDP)[2]. Urban areas face more congestion, and many cities have implemented car banning policies in their centres. Furthermore, in order to align with the Paris Agreement[3], and to limit global warming due to climate change to 2°C by 2050, the European Parliament endorsed the net-zero greenhouse gas emissions objective in its resolution on climate change in March 2019[4] and resolution on the European Green Deal in January 2020[5]. Given these challenges, it is evident that an over-dependency on road-based transport is not sustainable to address the growing demand for freight transport. Therefore, it is imperative for Europe to actively pursue and invest in alternative modes.

The massive under-exploitation of Inland Waterways (IWW) in Europe, especially in and around urban areas, represents a significant opportunity. According to the European

Commission[6], the average external costs for inland waterway freight transport, when considering congestion, is 1.9 €-cent/tonne-kilometer (tkm). The corresponding value for light goods road vehicle (gross vehicle weight under 3500 kg) is between 22.3–24.7 tkm, while for heavy goods road vehicle (gross vehicle weight above 3500 kg), it is 4.2 tkm. Furthermore, transporting goods via waterways is regarded as a more environmentally friendly mode of transport compared to road freight transport. In cities with dense, widespread waterway networks, a considerable portion of freight transport can shift from road to water, resulting in a significant reduction in external costs and greenhouse gas emissions.

Despite the potential of small IWW, the transported freight volumes on these waterways in Europe shows since 1977 an overall decrease and these markets are losing share to road haulage[7]. To a great extent, the decline is caused by the fact that vessels of the European Class type I and II (often referred to as CEMT I and II) operating in small IWW are currently not economically viable. The negative investment climate is attributed to various factors, including high crew cost, a declining number of young skippers, high entry and exit barriers, and a lack of technological advancements[7]. These issues can be remedied through increased automation, reducing the dependency on highly skilled helmsmen and modernizing the IWW freight transport mode. Therefore, increasing automation level of the vessels is part of the solution that ensures a sustainable and promising future for the exploitation of small IWW.

In this context, an autonomous urban cargo vessel prototype, named the *Maverick*, has been designed and built. It will be serving as a test bed to develop, test, and evaluate suitable technologies. The remaining paper is organized as follows: Section 2 outlines the industrial relevance of the *Maverick*, and identifies the distinct features of it in comparison to other existing test beds. Subsequently, Section 3 discusses the design details of the vessel, including (i) vessel type and geometry, (ii) actuation system, (iii) modular hardware design. Furthermore, Section 4 provides details of several trail tests, encompassing (i) maneuverability-related navigation data, (ii) cooperative interactions between different systems during autonomous sailing. Finally, Section 5 concludes this paper and discusses the future research areas.

2. Industrial relevance

This section elaborates on the industrial application that underlines our design decision regarding the *Maverick*. Additionally, other existing test beds are introduced and the exceptional features that set the *Maverick* apart from others are clarified.

2.1. AVATAR project

The *Maverick* is designed within the framework of the European project AVATAR. With its full name '*Sustainable urban freight transport with autonomous zero-emission vessels—modal shift from road to water*', AVATAR aims to deploy zero-emission automated vessels that perform hourly traffic between the urban consolidation centres outside the city and inner city hubs, focusing on the distribution of palletized goods and waste return[8]. With this objective, AVATAR project unlocks the economic potential of urban cargo vessels and corresponding waterways, increases available solutions for full-cycle automation and sets up a sustainable supply chain model. The *Maverick* is not only used to develop and test related technologies, but also serves as a valuable platform to evaluate the business case.

2.2. Relating test beds

The field of mechatronics is advancing, unlocking greater potential for semi- or fully-autonomous surface vessels. Several prototypes have been built for environmental monitoring missions and ocean resource exploration[9, 10, 11, 12, 13]. Efforts towards autonomous inland ferries are also noteworthy, Norwegian University of Science and Technology developed an autonomous ferry prototype, named the *milliAmpere*[14]. Building upon the experiences gained from this test bed, the full-scale autonomous ferry *milliAmpere2* was successfully launched. In terms of the autonomous cargo vessels, Moreira and Guedes Soares[15] utilized a scaled model of a sea-going vessel to perform maneuvering tests autonomously. However, industrial application of this vessel is still lacking. National University of Singapore designed a small cargo vessel specifically for short-sea operations to facilitate offshore maritime shipping[16]. In recent years, inland cargo vessel has became first movers regarding the autonomous freight shipping and a few test beds have been built with a greater emphasis on commercial markets. KU Leuven developed an unmanned inland cargo vessel named the *Cogge*[17] by scaling down European Watertruck+ project vessel[18]. Preliminary unmanned sailing experiments were carried out successfully, but the *Cogge* cannot carry cargo, and hence, is less suited for more realistic operating conditions. Another European project AUTOSHIP[19] tries to deploy new equipment on an existing inland barge to upgrade its capability to operate with increased autonomy. The development of these prototypes showcases the growing interest in leveraging autonomous technologies for efficient and sustainable operations on waterways. The *Maverick* distinguishes itself from the other test beds mentioned above by specifically targeting an urban context. The vessel size and type of the *Maverick* has been chosen accordingly to meet the waterway restriction and to improve vessel stability and maneuverability. Moreover, the *Maverick* can carry cargo and is deployable in realistic transporting scenarios. This feature allows researchers to not only focus on autonomous sailing but also to identify and address challenges related to cargo handling and transshipment. The *Maverick* represents a further step and refinement regarding the development of autonomous inland shipping by focusing on the adoption and integration of itself into urban transportation networks.

3. Design

This section describes the principal design aspects of the *Maverick* as follows: (i) Vessel type and geometry, (ii) Actuation system, and (iii) Modular hardware design. The motivation of the design choices are clarified.

3.1. Vessel type and geometry

The *Maverick*'s hull form is chosen to be a catamaran. Compared to monohulls, catamarans are seldom chosen to transport cargo for the following drawbacks:

- Smaller displacement and resultant lower carrying capacity.
- Lower structural strength due to the separated hulls.
- Incompatible with port equipment developed for monohulls that prevails in major harbours.

However, given the development aims mentioned in Section 2, these drawbacks seldom exist for the *Maverick*'s intended applications. For the small urban cargo vessel concept we advocate here, their aimed carrying capacity only ranges from 1–100 tons. The relatively low demand on carrying capacity suggests that using catamarans as cargo vessels is feasible. Furthermore, barely any cargo vessels are operating in urban areas, new supply chain mode and infrastructures are still under development. This gap in the market presents an opportunity to integrate catamaran hull forms into the new landscape of urban transportation. On the other hand, advantages of a catamaran perfectly meet the design requirements:

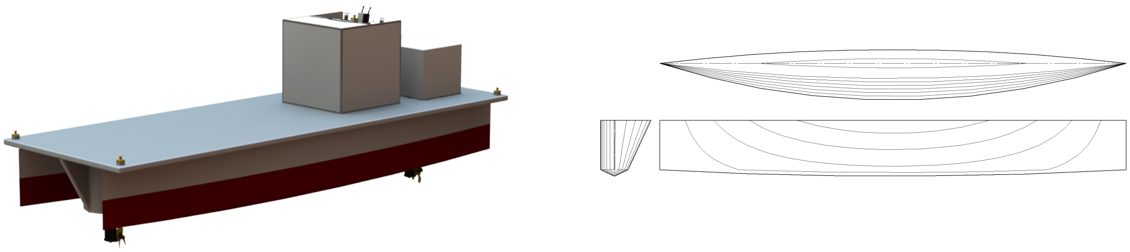
- Large open deck area: The designed vessel will need to carry different types and shapes of cargo rather than merely standardized cargo. Putting the cargo directly on the deck allows more flexibility, and the wide deck area of a catamaran increases this flexibility to a higher level.

- High transverse stability: The metacentric height of a catamaran is naturally higher than a monohull, and thus equips the *Maverick* with good stability. This allows the *Maverick* to sail more safely and to handle cargo more efficiently.
- Good maneuverability at low speed: A vessel that runs in urban area and performs hourly traffic frequently operates in low-speed conditions, where a catamaran hull form is preferable to ensure good maneuvering performance.

The main particulars of the *Maverick* are given in Table 1. The *Maverick*'s 3D model, together with the body plan of its demi-hull are shown in Figure 1 to demonstrate its geometric shape.

Table 1: Main particulars of the *Maverick*.

Particular	Symbol/Acronym	Values	Units
Length overall	LOA	6.10	m
Breadth overall	B	2.02	m
Breadth demi-hull	b	0.66	m
Separation distance	S	0.64	m
Moulded depth	D	0.73	m
Light draught	d_{light}	0.30	m
Loaded draught	d_{loaded}	0.60	m
Light displacement	Δ_{light}	903	kg
Loaded displacement	Δ_{loaded}	2329	kg



(a) 3D model

(b) Body plan of the demi-hull

Figure 1: Geometric shape of the *Maverick*.

3.2. Actuation system

The *Maverick* is equipped with 2 identical electric azimuth thrusters (SDK-ED 2.5 AC), one at the bow and one at the stern, mounted inside two cylindrical cabins that are located at the center line under the bridge deck. The detailed placement of the thrusters is shown in Figure 2. The configuration of the thrusters in the *Maverick* renders it over-actuated, enabling the execution of distinctive maneuvers, including pivoting around itself and parallel docking. The enhanced maneuverability of the *Maverick* makes it particularly well-suited for navigating inside the narrow urban waterways.

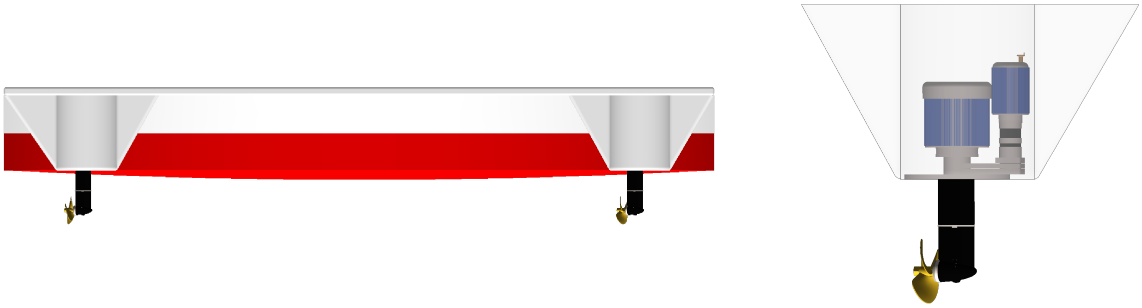

(a) (b)

Figure 2: Side view of the *Maverick* without starboard demi-hull (a), and partial view of the thruster mounted in the cylindrical cabin (b).

3.3. Modular hardware design

As a research vessel, the design principle of the *Maverick* focuses on adaptability to different console terminals and extensibility for future development. In this case, the hardware architecture of the *Maverick* is deliberately structured within a modular system characterized by a flexible and resilient interface. This design principle enables the *Maverick* to effectively serve varied research objectives, accommodating different equipment and data acquisition systems, allowing for the incorporation of advanced technologies.

The hardware modular system consists of actuation control subsystem, battery management subsystem, and autonomy subsystem. The components and their links are illustrated in Figure 3. The actuation control subsystem directly regulates the function of the thrusters. The *Maverick*'s azimuth thrusters are each controlled by a pair of identical programmable AC motor controllers (Curtis 1232E-2321), which manage the shaft rotation angle and motor revolution, respectively. These motor controllers transmit the real-time states of the thrusters to the Programmable Logic Controller (PLC), while receiving the control commands from the PLC through the CAN communication protocol. The autonomy subsystem of the *Maverick* is dedicated to enhancing the automation capabilities by leveraging data from the other two subsystems, as well as external devices. By integrating ports into the switch and PC, the autonomy subsystem gains the flexibility to support a wide range of peripheral equipment, such as Industrial PC, Global Navigation Satellite System (GNSS), Inertial Measurement Unit (IMU), Radio Detection And Ranging (RADAR), and Light Detection And Ranging (LiDAR). Moreover, to enable seamless integration of the autonomy subsystem with various control consoles, all types of data can be efficiently communicated to different terminals using either the switch or the modem. The *Maverick* also simplifies the process of connecting external PCs from multiple users through the Human-Machine Interface (HMI) of the PLC, ensuring rapid connectivity.

With its modular design, the *Maverick* exhibits exceptional versatility in accommodating different sensor setups. Unlike other test beds that rely on integrated onboard sensors, the *Maverick* treats sensors as external devices rather than fixed internal components. This design approach allows the *Maverick* to effortlessly adapt to specific requirements and enables future upgrades or replacements without significant modifications to its core structure. Currently, an integrated mobile sensor box comprising Industrial-PC, GNSS, IMU, and LiDAR is mounted to the *Maverick*. In addition, camera and RADAR are connected through switch to support perception function. These external devices have been successfully utilized in the current setup. An autonomous sailing test using this configuration is described in the subsequent section.

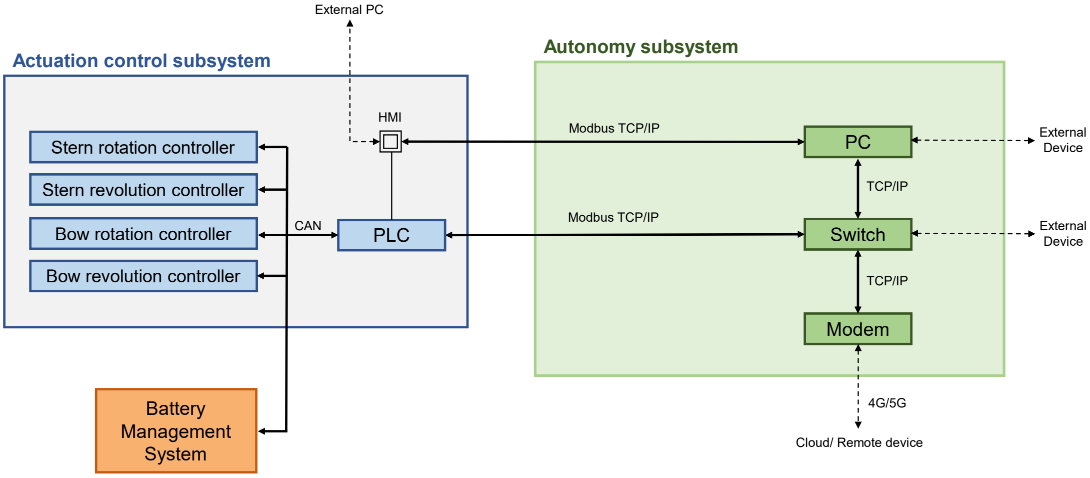


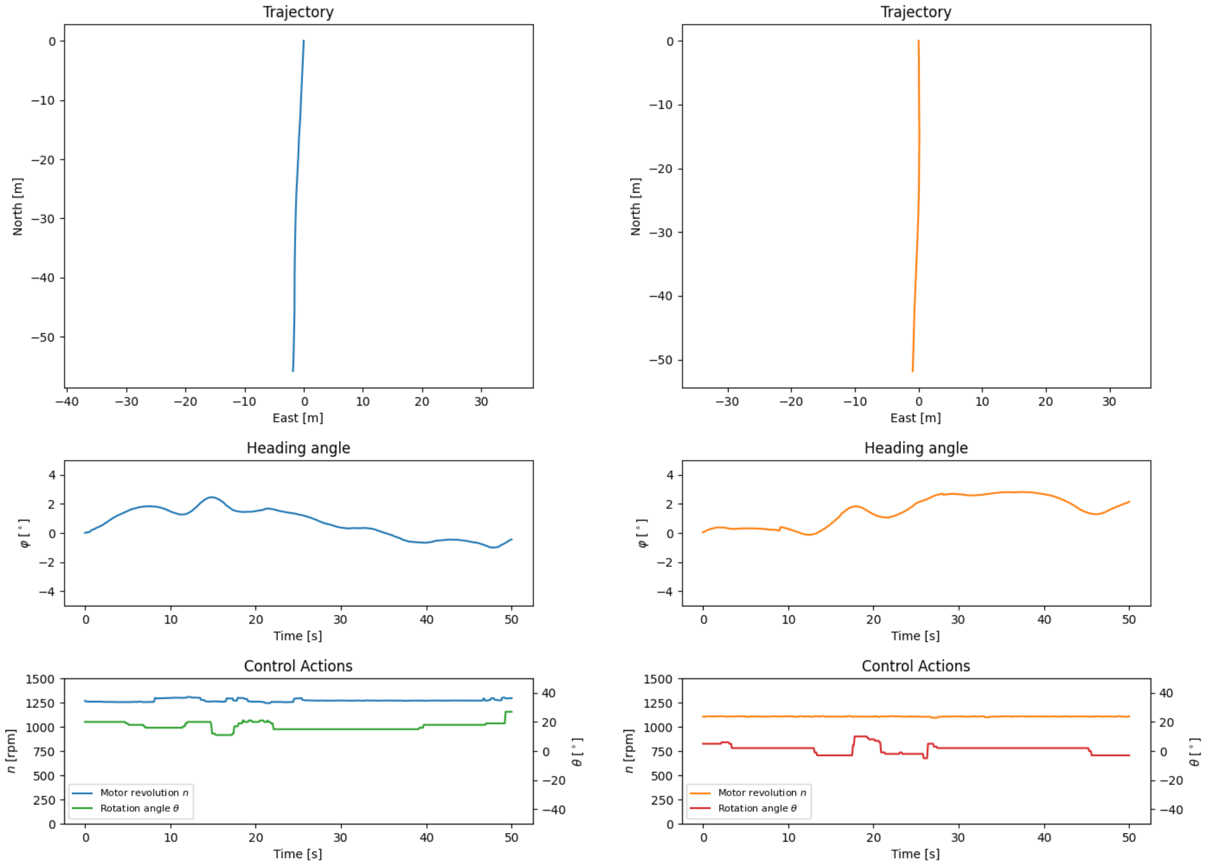
Figure 3: Overview of the hardware modular system and its inter- and intra-communication links, where the blue parts are the low-level control devices, the green parts include communication and computation components, and the orange part is for battery management.

4. Experiments

This section presents the first round of experiments conducted with the *Maverick* to demonstrate its potential of operating on small inland waterways. All the trials are committed on the canal from Leuven to the Dyle (*Kanaal Leuven — Dijle*). Firstly, straight-line sailing tests of the *Maverick* are presented to evaluate its course-keeping ability. Afterwards, an overview of an autonomous sailing trial is provided, together with the collaborative interplay among various systems.

4.1. Straight-line sailing

In the process of conducting the straight-line sailing tests, a skilled onboard captain controlled the *Maverick*, employing visual observation to maintain a consistent straight-line trajectory. The tests involved two distinct sets of experiments, one relying solely on the bow thruster and the other solely on the stern thruster. Figure 4 shows the sailing performance of the two actuation settings, along with their corresponding control actions. Both the trajectory and heading angle derived from these tests indicate that the *Maverick* is able to maintain a straight path without excessive oscillations of control or heading. However, a discernible performance difference between the two actuation settings can be observed. Notably, in order to achieve similar velocity, a higher motor revolution needs to be given using the bow thruster compared to using the stern thruster. This divergence, in turn, translates to a higher consumption of energy. To be specific, the energy expenditure using the bow thruster is 0.356 $\text{kWh}\cdot\text{km}^{-1}$, while a more economical value of 0.289 $\text{kWh}\cdot\text{km}^{-1}$ for using the stern thruster. Furthermore, during the tests we found that the *Maverick* is not dynamically stable while using the bow thruster with a neutral position close to midship. A neutral helm is found at 20 degree of rotation angle towards the starboard side, which can be seen in Figure 4a. The underlying causes of this phenomena are still under investigation. One plausible explanation put forth by the authors is that the demi-hulls of the *Maverick* are not placed precisely symmetrical, leading to an asymmetrical flow filed around the hull. At the mean time, the turbulent flow emanating from the bow propeller plane aggravates the non-symmetric phenomena on the forces acting on the *Maverick*.



(a) (b)

Figure 4: Straight-line sailing using solely the bow thruster (a), and using solely the stern thruster (b).

4.2. *Autonomous sailing*

During the autonomous sailing trial, the *Maverick* was deployed in a realistic cargo transport scenario with a waypoint path controller. Figure 5 depicts the *Maverick* in action, with a captain hands off-wheel and a bag of cargo on the deck. The interactive communication framework between different systems is summarised in Figure 6. The central component of this framework is the message-oriented middleware: Neural Autonomic Transport System (NATS). The core functionalities of NATS are publish/subscribe with subject-based-addressing and queuing. These features facilitate effortless construction of distributed and scalable client-server applications, while also enabling the efficient storage and real-time distribution of data in a general manner. This flexibility extends across diverse environments, programming languages, cloud providers, and on-premises systems[20]. In the context of sensor data acquisition, all data collected by various devices is directly routed to NATS and subsequently distributed as per requirements. For control function, the controller retrieves the list of predefined waypoints directly and reads current vessel states from NATS. Upon computation, the controller transmits the desired control actions to NATS, which in turn directs them to the PLC to effectuate control over the thrusters. To monitor the power consumption and system operating status, the battery management system communicates voltage, current and capacity of each battery to the PLC. In parallel, the PLC sends current motor states and battery states to NATS. The final link of the framework is a visualization module developed by Mappalink[21]. All data retrieved by NATS, along with external input from an electronic navigation chart are streamed to this module. Here, live-stream clustered point cloud data is combined with the local map to provide an integrated view of the surroundings. With the developed technologies, the *Maverick* successfully followed the desired path and navigated through two bridges.

Figure 5: Human onboard autonomous sailing test[22].

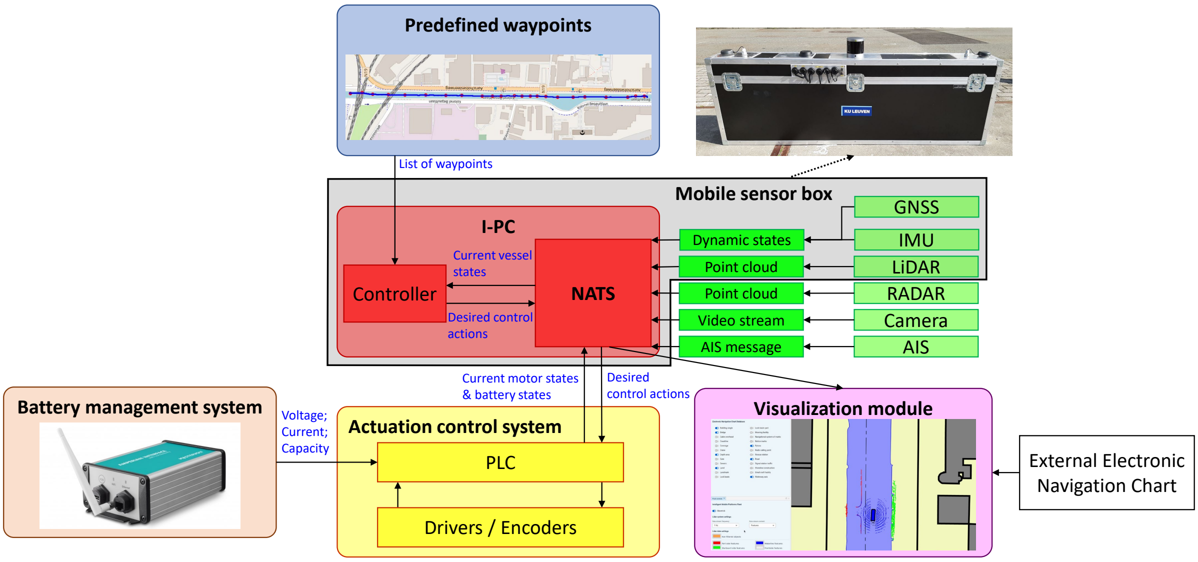


Figure 6: Interactive communication framework.

5. Conclusion and future research

To summarize, this paper presents a novel test bed which aims to develop and evaluate suitable technologies to increase the level of automation of inland vessels, also to explore and implement innovative solutions that can unlock full potential of waterborne freight transport in urban environments. The presented vessel features a catamaran hull form, which facilitates efficient cargo handling. It incorporates azimuth actuation systems to enhance maneuverability and broaden control options. Additionally, the vessel is equipped with a modular hardware setup, enabling easy adaptation to different operational requirements. The integration of these design elements yields a comprehensive communication framework between each system. Successful execution of the preliminary maneuverability-related tests and autonomous sailing trials distinctly demonstrate the capabilities and potential of our design.

Although the *Maverick* is already launched and has performed some experiments, further improvements will be key to achieve higher levels of automation or even unmanned status for the vessel. Firstly, the hydrodynamic characteristics of the vessel have not yet been investigated. Building a maneuvering model would benefit the development of advanced control algorithms. Secondly, it's worth noting that the controller and middleware are currently exclusively implemented on the mobile sensor box, while the software architecture onboard the *Maverick* is still in the developmental phase.

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