The Maverick-vessel Assessment Report in an Urban Waterway

Within the framework of the Interreg NSR project AVATAR work package 5

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Colophon

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AVATAR - Maverick vessel assessment report

1. Introduction

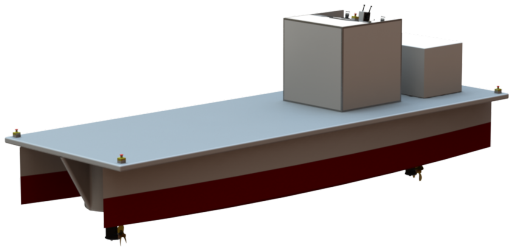
The *Maverick* is designed within the framework of the European project AVATAR. With its full name '*Sustainable urban freight transport with autonomous zero-emission vessels—modal shift from road to water*', AVATAR aims to deploy zero-emission automated vessels that perform hourly traffic between the urban consolidation centres outside the city and inner city hubs, focusing on the distribution of palletized goods and waste return.

The vessel size and type of the *Maverick* have been chosen accordingly to meet the waterway restriction and to improve vessel stability and maneuverability. The *Maverick* is able to carry cargo with it and be deployed 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. Furthermore, 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.

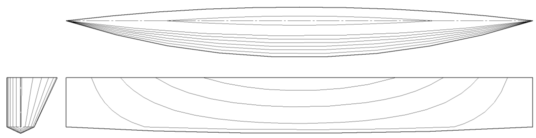
The *Maverick*'s hull form is chosen to be a catamaran. The main particulars of the *Maverick* are given in Table 1. The *Maverick*'s 3D model, together with the body plan of its demi-hull are shown in Figure 1 to demonstrate its geometric shape. The *Maverick* has two identical electric azimuth thrusters (SDK-ED 2.5 AC), one at the bow and one at the stern, mounted inside two cylinder cabins located at the center line under the bridge deck. The placement of the thrusters is shown in Figure 2.

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_m	0.73	m
Displacement volume	Vol	1	m^3
Propeller diameter	D_p	0.3048	m
Maximum propeller rate	n_f	1860	rpm
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



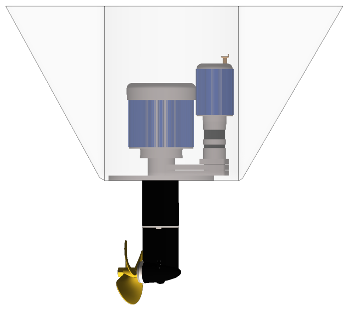
(a) 3D model



(b) Body plan of the demi-hull

Figure 1: Geometric shape of the *Maverick*.

(a)



(b)

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

2. Manoeuvring tests

The Manoeuvring tests of the *Maverick* are conducted by manual operations with an onboard captain on the canal Leuven Vaart. During the tests, the motion states were recorded with a GNSS/INS integrated sensor deploying on the *Maverick*. The position data from GNSS module are corrected with the RTK base station, which can reach the centimeter accuracy. The pose data are generated from the integrated sensor unit with a built-in Kalman filter fusing the data from GNSS and IMU. These data were collected during the tests to evaluate the manoeuvrability of the *Maverick*. The wind speed and flow current were not collected during the tests.

2.1. Navigate in straight line

In the straight line sailing tests, the onboard captain controlled the *Maverick* and kept the ship moving straight by eye observation. Meanwhile, the captain tried to keep a constant course speed during the tests. The straight line test is subjective and the result highly depends on the captain's cognition of moving. The tests are varied by different actuation sets, which are divided into three setups, operating both bow and stern thrusters, only operating the bow thruster, and only operating the stern thruster. The ship motion trajectories for each setup are shown in Figure 3. Notably, due to the onboard manual operation with eye observation, there is no pre-defined reference line as the ground truth for evaluation. Hence, the least square regression is adopted here to fit a straight line as the reference. The fit scores are shown in the images, which represent the coefficient of determination ranging from 0 (worst) to 1 (best).

From the trajectory picture, manoeuvring with only one thruster has a significantly better performance than the operation with two thrusters, where the stern operation one has the highest line fitting score. Figure 4 demonstrates the ground speed and the average power in the straight sailing operation. During each test, the captain was trying to keep the *Maverick*'s speed around at 1 m/s. In straight line manoeuvring, it shows that it's easier to keep a constant speed with only one thruster. Furthermore, manoeuvring with the stern thruster needs the least average energy power 1088.7 $watts$. Additionally, the energy consumption of the three setups (Bow&Stern, Bow, Stern) is 0.364 kWh/km, 0.369 kWh/km, and 0.302 kWh/km, respectively. Figure 5 illustrates the motor states in terms of the different tests, where the oscillations in the state curves can be originated from the dynamic wind and flow current. In summary, operating only the stern thruster reached the best performance in this test according to the highest line fitting score and lowest energy consumption.

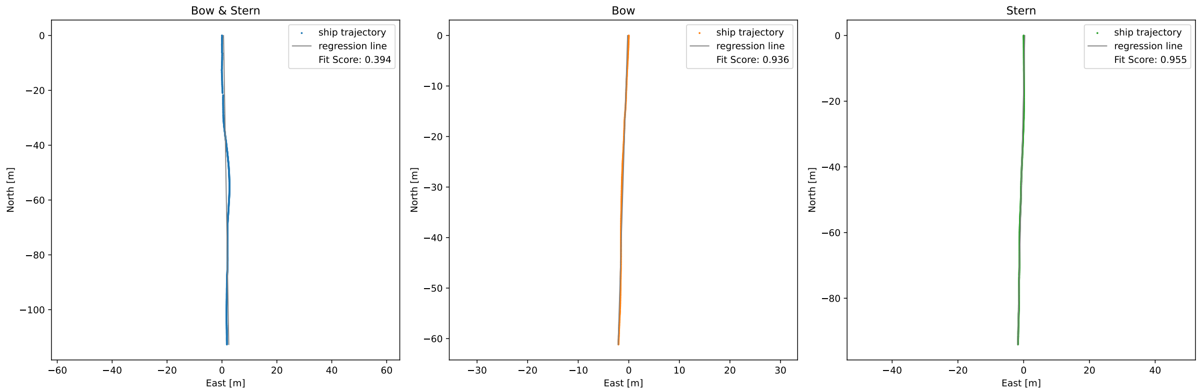


Figure 3: Manually sail the *Maverick* in straight line. The trajectory points are in a local East-North frame, where the horizontal axis represents the East and the vertical axis represents the North direction. The origin point is the initial position of the *Maverick* in the trajectory. The values on both axes are in meter units.

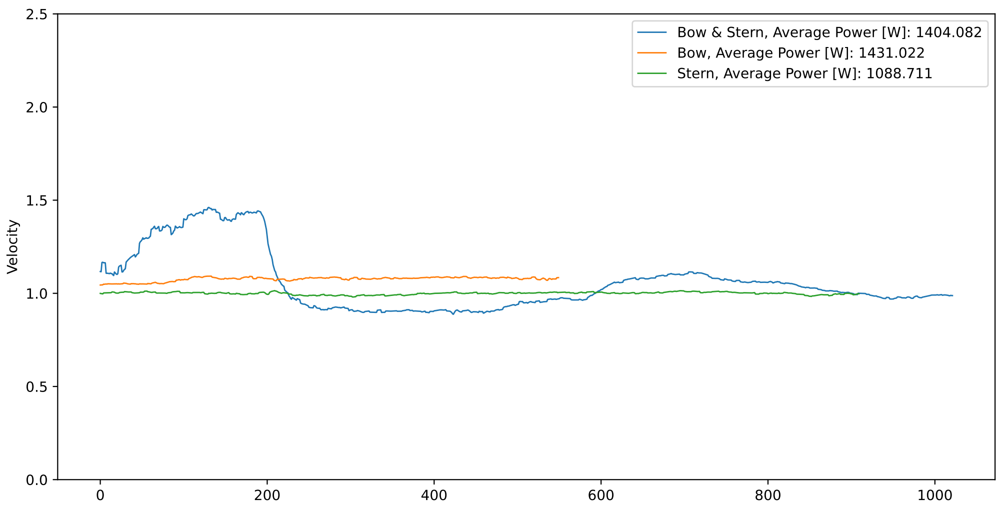
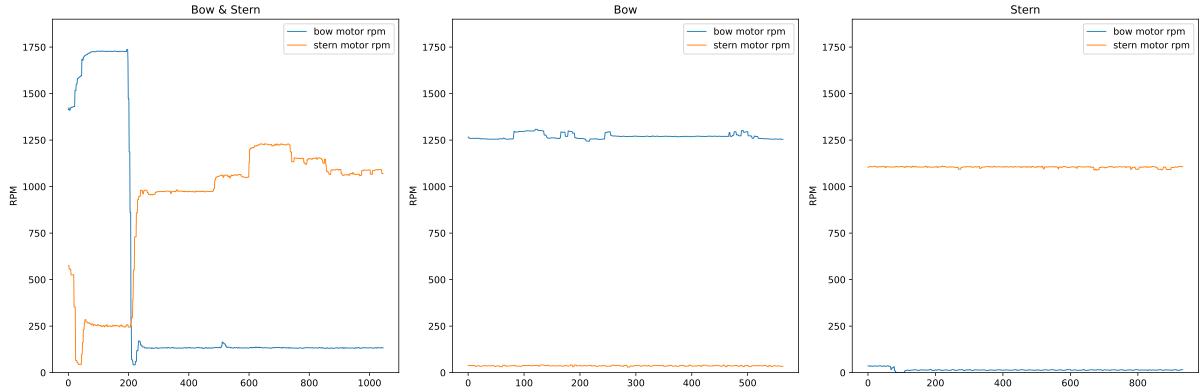
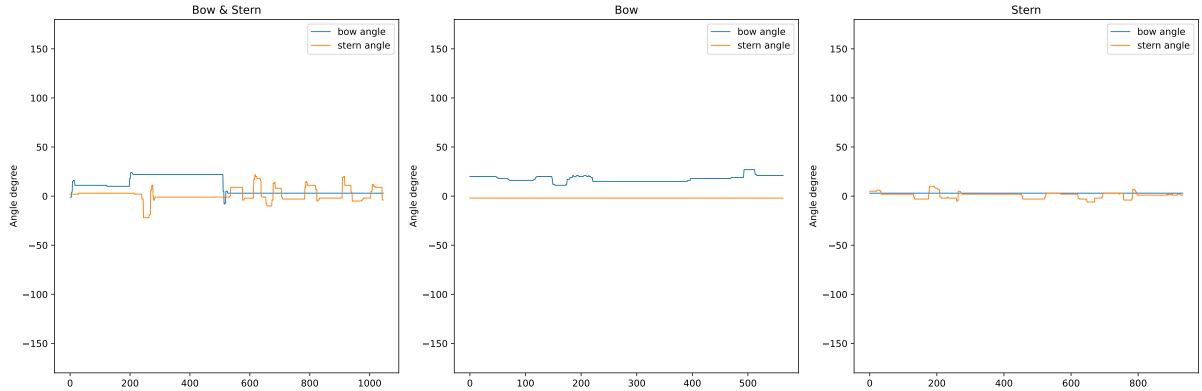


Figure 4: Ground speed and average power. The horizontal axis represents the time steps that are sampled in 10 Hz. The velocity axis represents the ground speed with a meter per second unit.



(a) Propeller rotation speed in rpm.



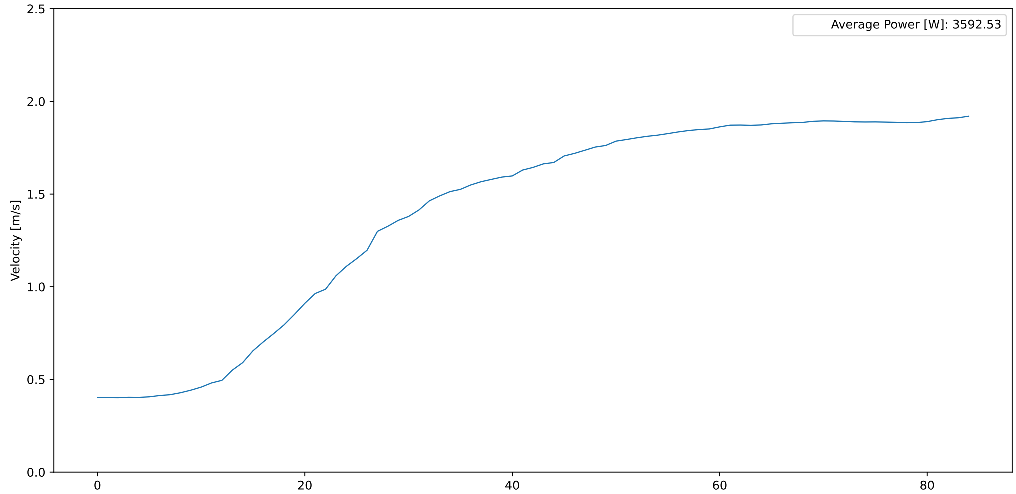
(b) Thruster angle in degrees. 0 value means the propeller is aligned with the ship's longitudinal axis and towards the backside. In the top view, the clockwise rotation is positive.

Figure 5: Bow and stern thrusters' states during moving straight. The blue curve is for the bow thruster, and the orange curve is for the stern thruster. In each sub-figure, from left to right are manoeuvering with two thrusters, with bow thruster, and with stern thruster.

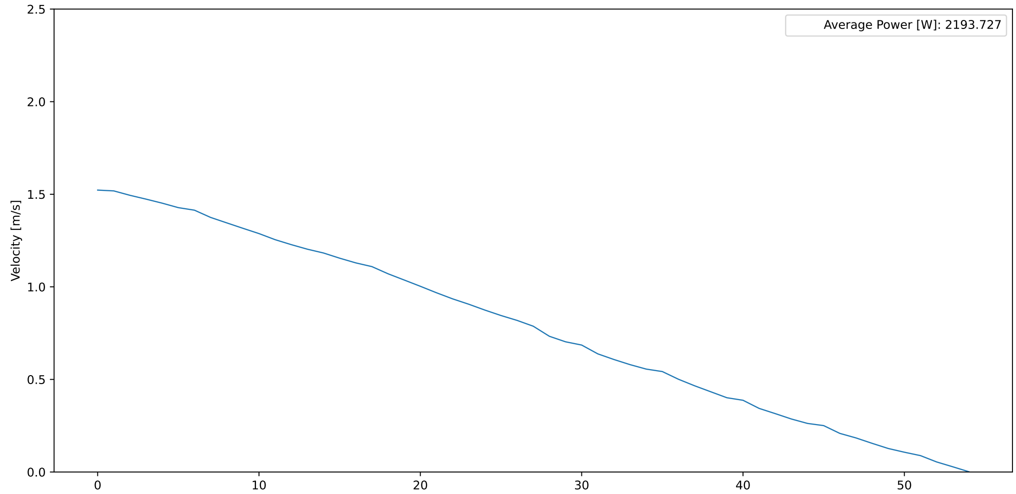
2.2. Acceleration and deceleration

In the acceleration test, the *Maverick* first reached a constant speed of 0.4 m/s. Then, the bow and stern propellers rotated from zero to maximum rpm for acceleration. As shown in Figure 6a, the acceleration takes around 8 *seconds* from the ground speed of 0.4 m/s to reach the maximum ground speed of 1.92 m/s, where the propeller takes around 4 *seconds* to reach the maximum rotation speed of 1860 *rpm*. The average power of the acceleration is 3166.788 *watts* and the acceleration distance is 12.388 *meters*.

In the deceleration test, the *Maverick* first reached a relatively high constant speed of 1.56 m/s with only the stern thruster. Then, it started the deceleration until stop. The changing of the speed is illustrated in Figure 6b. In this test, only the stern thruster was used for deceleration and it took around 5.5 *seconds* to stop the *Maverick* with the average power of 2193.727 *watts*. Additionally, the length of track was 4.34 *meters* which is less than the length of the *Maverick*.



(a) Velocity during the acceleration.



(b) Velocity during the deceleration.

Figure 6: *Maverick*'s velocity curves with time steps sampled in 10 Hz as the horizontal axis during accelerating to maximum ground speed and decelerating to stop.

2.3. Turning circle

For the turning circle, the *Maverick* first reached a constant speed with zero angles of both thrusters. Then, the bow thruster angle was kept to zero while the stern thruster angle was manually set to a fixed value through the joystick on the console of the *Maverick*. To the thruster angle, the number 0 means the propeller is aligned with the ship's longitudinal axis and towards the backside. In the top view, clockwise rotation about the vertical axis (cylinder axis) leads to a positive angle.

Here, two turning tests were conducted with two different sailing speeds: 1 m/s and 1.6 m/s. The stern thruster angle was planned to be 35 *degrees* for both tests. However, due to human operation errors, while rotating the joystick, the real angle deviated from the target value. The two moving trajectories are illustrated in Figure 7, where the origin point in the local coordinates represents the starting position.

- Circle with 1 m/s: The tactical diameter is 18 *meters* and turning radius is 7.75 *meters*.

The stern thruster angle is around 39 *degrees*. The average power is 2050.6 *watts*.

- Circle with 1.6 m/s: The tactical diameter is 24 *meters* and turning radius is 10.74 *meters*. The stern thruster angle is around 35 *degrees*. The average power is 4844.649 *watts*.

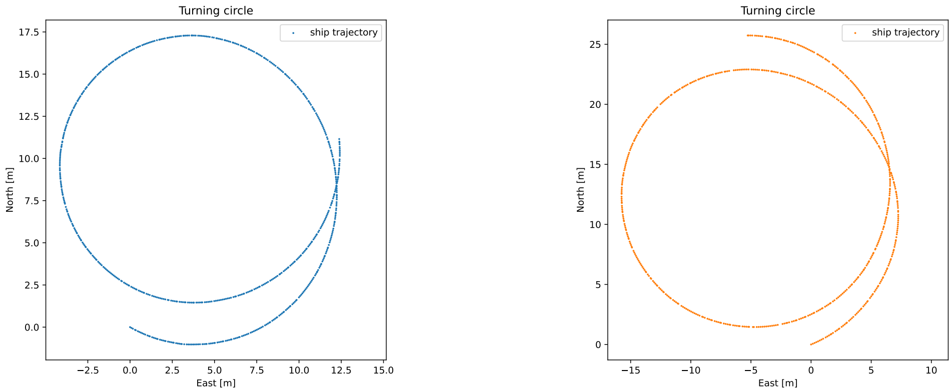


Figure 7: Motion trajectories during turning circle with different speed. Left: 1 m/s; right: 1.6 m/s.

2.4. Zig-zag

According to International Maritime Organization (IMO) standards, "a zig-zag test should begin by applying a specified rudder angle to an initially straight approach. The rudder angle is then alternately shifted to either side (starboard or port) after a specified deviation from the ship's original heading is reached". Since the *Maverick* does not have a rudder, the thruster angle is adopted here instead of the rudder angle. Moreover, two kinds of zig-zag defined in the standard are included: 10°/10° zig-zag and 20°/20° zig-zag.

Due to the limitation of the experimental environment, the narrow canal Leuven Vaart, bow thruster was not able to complete a zigzag test. Therefore, only the stern thruster manoeuvre of the *Maverick* was evaluated in this section. During the tests, the *Maverick* first reached a stable speed only using the stern thruster with a specified rotation speed of the propeller (1000 rpm) in a straight approach. Then, the thruster angle was changed according to the zig-zag angle and the reaching of the heading. Because of the manual operations with the onboard joystick, the errors between desired and actual propeller rotation speed, as well as desired and actual thruster angle can be observed in the results.

- 10°/10° zig-zag: The actual propeller speed is around 960 rpm. The heading and thruster angle are shown in Figure 8 & 9. The maximum overshoot angles on the starboard and port side are 11.06° and 5.86°, respectively. The *Maverick* has a larger overshoot on the starboard side than the port side.
- 20°/20° zig-zag: The actual propeller speed is around 970 rpm. The heading and thruster angle are shown in Figure 10 & 11. The maximum overshoot angles on the starboard and port side are 8.25° and 13.4°, respectively. Notably, the fourth heading overshoot on the port side is excluded due to a large error in the thruster angle. In this zig-zag, the *Maverick* has a larger overshoot on the port side, which is in contrast to the 10°/10° zig-zag test.

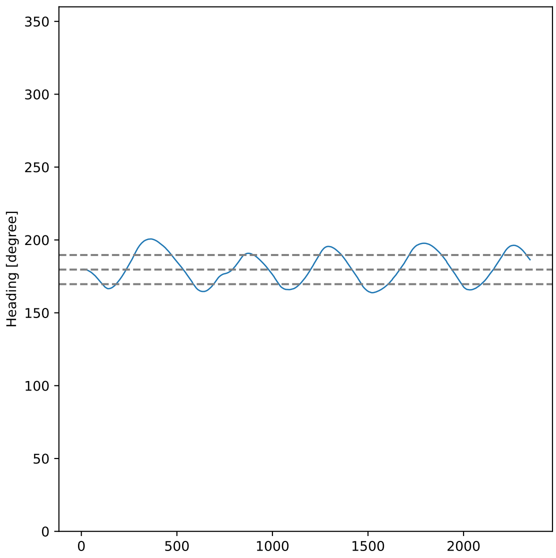


Figure 8: Zigzag 10/10 - Heading. The top dashed grey line represents the starboard side 10° heading deviation; the middle dashed grey line represents the initial heading; the bottom dashed grey line represents the port side 10° heading deviation.

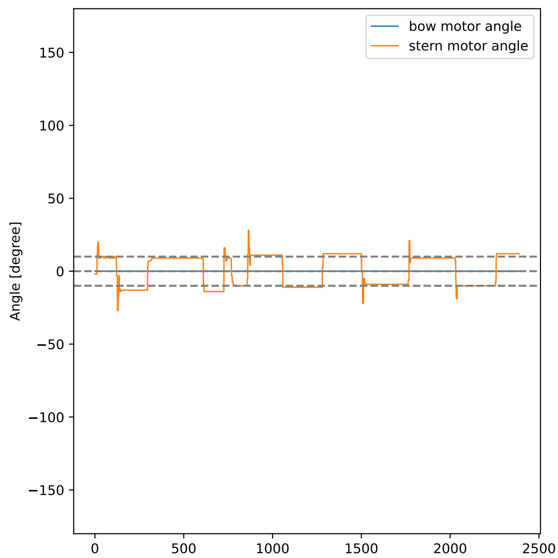


Figure 9: Zigzag 10/10 - Thruster angle

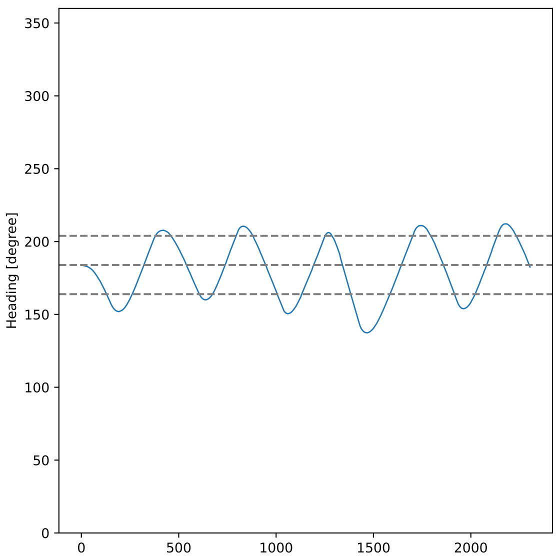


Figure 10: Zigzag 20/20 - Heading. The top dashed grey line represents the starboard side 20° heading deviation; the middle dashed grey line represents the original heading; the bottom dashed grey line represents the port side 20° heading deviation.

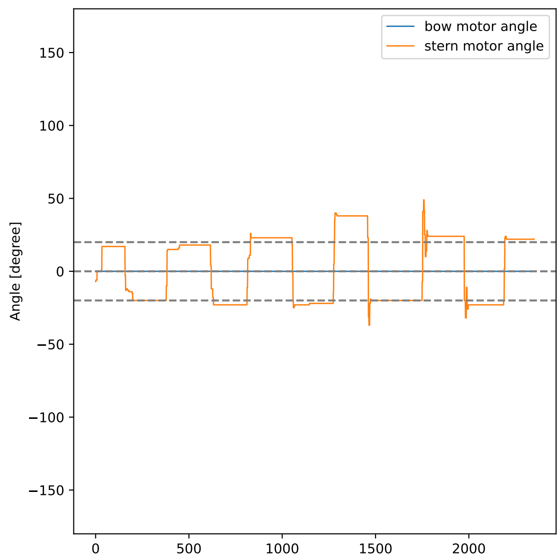


Figure 11: Zigzag 20/20 - Thruster angle

3. Control tests

In the control tests, a PID controller was adopted as the high-level control unit in the control module of the *Maverick*, which outputs the commands to, the low-level control unit, the onboard Programmable Logic Controller (PLC). During the automatic sailing, the control module receives the thrusters' states and the ship's geographic locations; considers the objective path defined by waypoints; and calculates the desired thruster's states as the commands sent to PLC.

3.1. Path following

In this test, a series of waypoints were manually selected in geographic coordinates. These waypoints defined the path that the *Maverick* needs to follow. Each sub-path between every two waypoints is treated as a straight line by the *Maverick*'s control module. Then, the *Maverick* automatically sailed to follow the defined path and waypoints. The motion trajectory was recorded based on a GNSS/INS sensor where the data were down-sampled to $10Hz$ frequency. The path/waypoints and the ship's motion trajectory are illustrated in Figure 12. During the path following, the *Maverick*'s speed was around 1.58 m/s and sailed around 660 $meters$ against flow current; the average power is 4072.585 $watts$ and the energy consumption is 0.71 kWh/km.

To evaluate the performance of the path following, the absolute residuals are calculated for trajectory points in terms of the path. The residuals represent the deviations of the *Maverick*'s motion to the defined path. It is computed as Eq. 1, where $\boldsymbol{r}$ denotes the absolute residual vector, $\boldsymbol{x}$ represents the vector comprising the values of each motion point on the north axis in the local coordinate system, $\boldsymbol{y}$ is the vector composed of the values of each motion point on the east axis in the local coordinate system, and f_p denotes the mapping function that transforms the motion north vector to the path east vector. Figure 13 shows the distribution of the residuals in a boxplot for 4036 recorded motion points. In the distribution, the median residual is 0.788 m, the first quartile (Q1) is 0.608 m, and the third quartile (Q3) is 0.997 m.

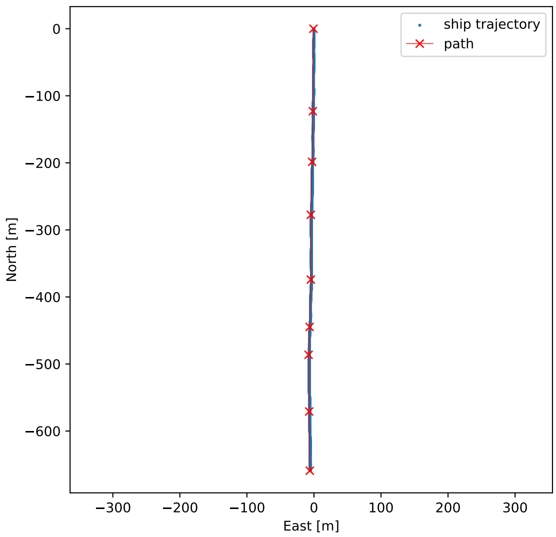


Figure 12: Path following around 660 $meters$. The target path is shown in a red curve where the red crosses are the waypoints. The ship's trajectory is in blue. The movement starts from the origin point.

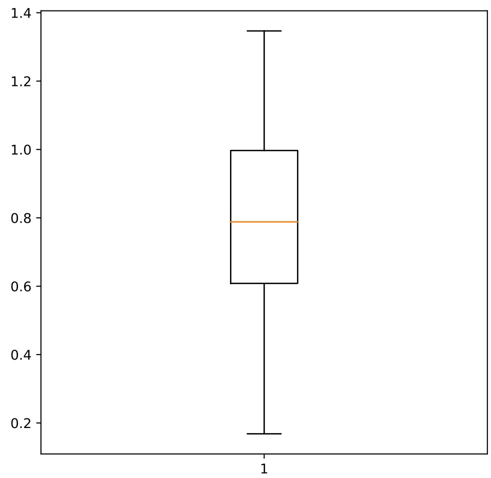


Figure 13: The distribution of the absolute residual in boxplot. Q1: 0.608 m; median: 0.788 m; IQR: 0.389 m; whisker: 0.5835 m.

$$\boldsymbol{r} = |\boldsymbol{y} - f_p(\boldsymbol{x})| \tag{1}$$

3.2. Course keeping and course changing

Here, we used three waypoints to define two path segments for the automatic course keeping and course changing. The waypoints and ship's motion trajectory are shown in Figure 14. The *Maverick*'s heading during the test is shown in Figure 15. In the two defined path segments, the objective course headings were 185 *degrees* and 210 *degrees*, respectively. On the other hand, when the *Maverick* followed the two paths, the actual average headings were 184 *degrees* and 206 *degrees*, respectively. In addition, the course changing time was around 9 *seconds*.

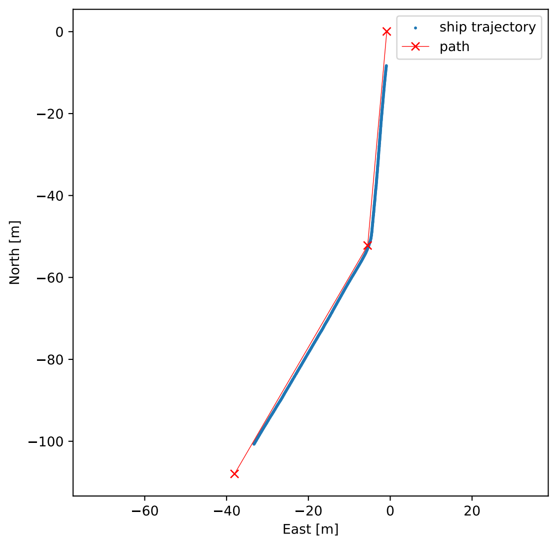


Figure 14: Motion trajectory and path of the course keeping and changing tests.

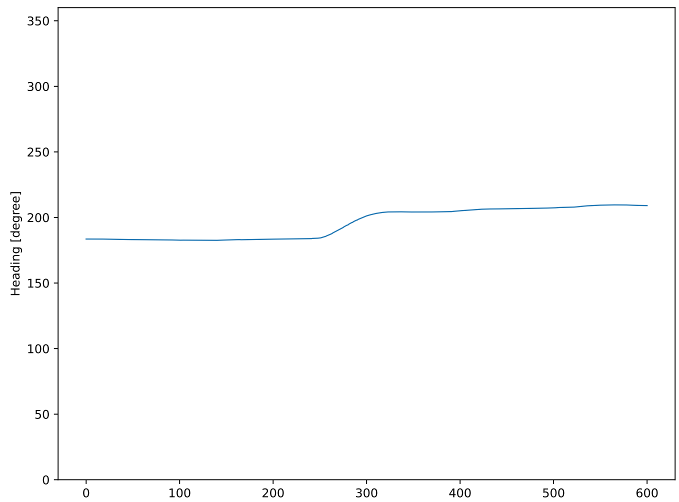


Figure 15: Heading curve of the course keeping and changing tests.

4. Remote control

Besides manual and automatic operations, the *Maverick* is also capable to integrate into a remote Shore Control Center (SCC) through the onboard cellular network unit. Generally, the *Maverick* transmits its states, including position, attitude, and the states of two thrusters, to the SCC using a message middleware. It then receives the desired new states for the thrusters from the SCC, which are subsequently fed into the PLC system for low-level control in terms of the actuators. Additionally, the *Maverick* is equipped with two IP cameras that capture the ship's surroundings, with the live video feed being streamed to the SCC.

In this remote control assessment, a remote captain was using an SCC to operate the *Maverick* with a 4G network connection. The captain has the ability to monitor various parameters of the ship, including heading, thruster rotation speed, thruster angle, speed of ground, attitude, position, and battery state of charge. Meanwhile, the captain can view the ship's surroundings through a video stream. Then, two azimuth joysticks on the SCC are used by the captain to control the *Maverick* manually, where the required thruster speed and angle can send to the *Maverick*. Throughout the test, the one-way latency experienced varied between 100 to 200 *milliseconds*.

Navigating in a straight line is chosen as the manoeuvering task because it is considered fundamental and allows for a more straightforward assessment of how latency affects the captain.

To simplify the operation, unlike the straight test in the section 2.1, here the captain used a fixed propeller rotation instead of maintaining a fixed speed of ground against the disturbance from wind and flow current. Two tests were conducted, using the bow thruster and stern thruster separately. In both tests, the propellers were operated at the same rotational speed (1000 rpm), ensuring consistency between the two tests. Once the ship achieved a relatively stable speed of ground, the captain initiated the straight line manoeuver by adjusting the thruster angle of the active thruster. Similar to the section 2.1, the performance is evaluated with a line fitting as well. The results are shown in Figure 16. Despite the lower line fitting scores obtained in this test compared to onboard manual straight line navigating, 11.65% decreased for stern and 6.28% decreased for bow, it still shows a good performance. The stern thruster achieved a score of 0.827, while the bow thruster achieved a score of 0.895.

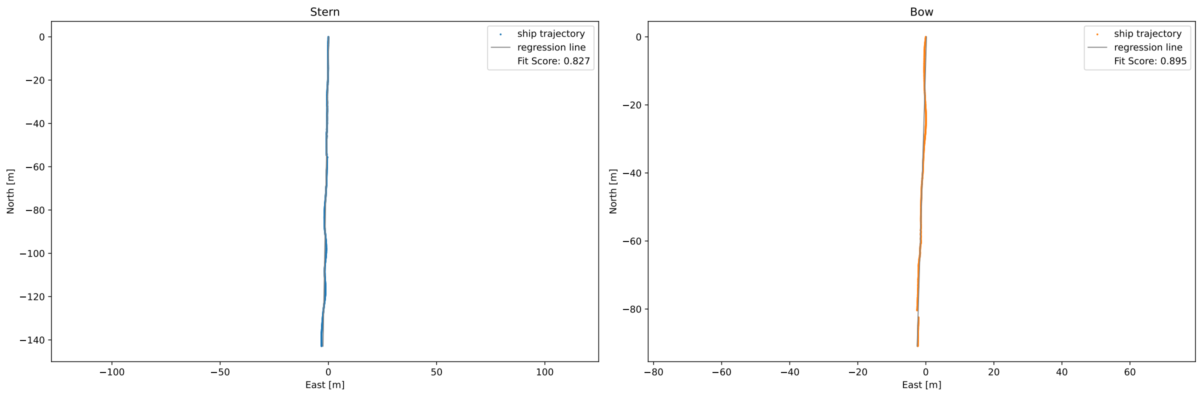


Figure 16: Remotely sail the *Maverick* in straight line. The trajectory points are in a local East-North frame, where the horizontal axis represents the East and the vertical axis represents the North direction. The origin point is the initial position of the *Maverick* in the trajectory. The values on both axes are in meter units.