Additional Test Manoeuvres for Autonomous Inland Vessels

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Abstract. Standardised test manoeuvres are used to identify the manoeuvrability of a vessel. Currently, most of these tests are unsatisfactory to properly judge the manoeuvring capabilities of an inland vessel which sails in different environments than the seagoing ships for which these tests were initially designed. Moreover, inland vessels tend to have non-conventional propulsion systems and configurations which further decreases the adequacy of these standardised tests. Therefore, this study investigates the inland-applicability of these existing standardised test manoeuvres. In addition, this study suggests three new manoeuvres: (i) the Counter Thrust Test, (ii) the Sine Angle Test, and (iii) the Simultaneous Zigzag Test. In order to validate the suitability of these tests, an autonomous inland cargo vessel performed two of these suggested manoeuvres, (i) and (ii), and one existing manoeuvre, named the Crabbing test. The data of these experiments show fruitful insights in the wide range of manoeuvring capabilities of the examined inland vessel, which the standardised tests would not have uncovered.

1. Introduction

The existing standardised test manoeuvres aim to reveal the capability of a vessel to perform certain manoeuvres. Hence, these tests allow for the identification of certain hydrodynamic manoeuvring characteristics and metrics. These characteristics can provide an operator with crucial information in order to take correct and timely decisions to safely and effectively navigate the vessel. The International Maritime Organization (IMO) issued the most-known manoeuvrability standards which include checking the manoeuvring performance of a vessel in terms of its inherent dynamic stability, course keeping ability, initial turning and course changing ability, yaw checking ability, turning ability, and stopping ability [1]. Note, however, that these IMO standards should be applied to "ships of all rudder and propulsion types, of 100m in length and over, and chemical tankers and gas carriers regardless of the length [1]". In Addition, the manoeuvring committee of the International Towing Tank Conference (ITTC) examined 19 manoeuvring tests proposed by various organizations and recommended procedures and guidelines for 14 of them which are able to measure the above-mentioned characteristics [2]. Currently, the most widely accepted tests for full scale trials consist of the Turning Circle Test, the 10/10 and 20/20 Zigzag Manoeuvre Test, and the Stopping Test.

However, the typical inland cargo vessel differs significantly from its seagoing counterparts. Firstly, inland cargo vessels tend to operate in spatially restricted shallow or confined water without the help of tug boats. Therefore, they are often built with multiple rudder and/or propeller configurations in order to boost their manoeuvring performance [3]. Even the addition of an azimuth thruster, or a transversal bow thruster, is not uncommon to further increase the manoeuvrability of a vessel [4]. Secondly, the vertical restrictions in the inland waterways usually result in speed regulations in order to avoid the touching of the bottom due to the arising squat effect. Hence, inland vessels usually perform their manoeuvres at low speeds and need to keep course under these conditions. Thirdly, due to the horizontal restrictions such as banks, heavy traffic in access areas, and the necessity of extreme close passages in narrow sections of canals, inland vessels also have to change their courses frequently and usually do a manoeuvre similar to cars changing lanes on the road [5]. Therefore, contrary to seagoing vessels where course keeping dominates, initial turning or course changing ability are crucial metrics for inland vessels.

Consequently, smaller vessels which navigate in shallow water with non-conventional propulsion types, do not directly fall under these above-mentioned IMO standards [4]. Therefore, some authorities, like the Central Commission for the Navigation of the Rhine [6] and the European Commission [7], offered regional standards for inland vessels [8]. Nevertheless, these regulations have fewer manoeuvrings tests and criteria and, therefore, the IMO standards are generally used as a guide for inland vessels [5]. To bridge this gap in adequate inland manoeuvres, [5] suggested additional manoeuvres and subsequent metrics for inland vessels. Thereupon, this work expands these additional inland manoeuvres and discusses the outdoor executions of some of these existing and newly added manoeuvres with an unmanned autonomous inland cargo vessel.

This paper continues as follows: firstly section 2 lists some of the existing standardised test manoeuvres, and afterwards it adds three new manoeuvres to this list. Section 3 details the design of the inland cargo vessel that conducted the experiments of section 4, based on which section 5 draws the conclusions of this study.

2. Method

Section 2.1 briefly discusses the existing manoeuvres which focus on non-conventional propulsion systems or inland vessels. Afterwards, section 2.2 introduces additional test manoeuvres tailored for inland vessels with non-conventional propulsion systems.

2.1. Existing Ship Manoeuvres

In the proposed guidelines of the ITTC, 2 of the 14 tests mention the use of a lateral thruster: (i) the *Thruster Test* suggests performing the turning or zigzag manoeuvre with the lateral thruster as a steering input and the rudder at midship, and (ii) the *Crabbing Test* suggests lateral movements at zero forward speed [2]. Furthermore, in the proposed tests for inland vessels of [5], the *Hard Turning*, *T-junction*, and *Lane Changing* tests can use, and benefit from, non-conventional thrusters and their position.

2.2. Suggested Additional Vessel Manoeuvres

Given the fact that inland vessels tend to use non-conventional propulsion configurations and non-conventional actuators, the here-suggested test manoeuvres assume a generic inland vessel which has two propulsion systems: one at the bow and one at the stern. Moreover, both propulsion systems are presumed to have a controllable thrust force magnitude, T, and orientation, θ. Evidently, the maximum thrust force depends on the geometrical design of the system and the engine powering it, whereas the limits of its orientation lie between $[0, 360]^{\circ}$. Or, more conveniently, one can denote this orientation by measuring the angle between T and the longitudinal axis of the vessel which points to the bow and encapsulate this angle between $[-180, 180]^{\circ}$ with a positive sign for counter-clock-wise angles. Accordingly, for the remainder of this study, $T \in [0, T_{max}]$, $\theta \in [-180, 180]°$, and the superscripts 's' and 'b' will be used to denote the stern and bow thruster respectively. Finally, it could happen that the internal control angle of the actuation system, θ_i, and the orientation of the resulting output force, θ_o, are not aligned, hence a differentiation will be made by using the subscripts 'i' or 'o'. Under these assumptions, the following three additional manoeuvring tests for inland vessels are suggested; 2.2.1: Counter Thrust Test, 2.2.2: Sine Angle Test, and 2.2.3: Simultaneous Zigzag Test.

2.2.1. Counter Thrust Test This test aims to locally rotate the vessel by covering as little space as possible. For this purpose, both the bow and stern thruster should try to exert an equal but opposite force. If the thrust forces do not be equal each other in magnitude, there will be a resulting lateral force which would make the vessel drift during the manoeuvre. Evidently, this manoeuvre could be performed in a clock-wise or counter-clock-wise turning direction, hence:

- $T^b = T^s$
- θ_i^b = 90° (or -90°)
- θ_i^s = -θ^b

2.2.2. Sine Angle Test This test helps to uncover the broad spectrum of achievable turning rates and thruster-angle changes. This test can be performed for both thrusters separately with the other thrusting providing no thrust at all or another desired value. Furthermore, both thrusters could perform the test simultaneously. The test parameters per thruster consist of its thrust magnitude, the maximum angle of its orientation, and the frequency of the sine function:

- T = chosen value
- $\theta = \theta_{max} \sin(2\pi f)$

2.2.3. Simultaneous Zigzag Test In line with the suggested additional zigzag manoeuvre from [2], where the lateral thruster provides the steering, one could also instruct both thrusters to work simultaneously. Towards this end, both thrusters should have an opposite angle to cooperatively perform the zigzag manoeuvre:

- T^b = chosen value
- T^s = chosen value
- θ^b = chosen value (e.g. 30°/-30°)
- θ^s = - θ^b

3. Material

The European Watertruck+ project is constructing a novel fleet of 31 inland cargo vessels of which 16 are self-propelled barges which have an over-actuated propulsion system enveloping a 360-degrees-steerable steering-grid thruster in the bow in combination with a 360-degrees-steerable 4-channel thruster in the stern [9]. The authors believe that these vessels exhibit a high potential for the further automation of their operations which could pave the way for future unmanned or even autonomous vessels. Consequently, to study this automation potential, they constructed a scale model of such a self-propelled barge [10, 11]. Figure 1a shows four real-size barges of European Class type I [12] which are being pushed by a push boat, and in Figure 1b the scale model, named '*Cogge*' can be seen sailing on the Yser river (in Belgium).

(a) (b)

Figure 1: (a) Four European Class type I vessels from Watertruck$^+$ pushed by a push boat [9], (b) The KU Leuven scale model, named Cogge [10].

3.1. Design of the Cogge

The Cogge has a length of 4.81m, a beam of 0.63m, and a maximal draft of 0.35m with a similar geometry as its Watertruck$^+$ counterpart. Figure 2a shows the 3-dimensional design drawing of the Cogge with the stern at the left and the bow at the right hand side of the image. The stern and bow thrusters can be seen on these respective locations. Thereupon, Figure 2b portrays an abstract top view of the four-channel stern thruster together with its angle convention, and Figure 2c illustrates the steering-grid thruster and its analogous angle convention. Both thrusters have a propeller which draws water from underneath the hull, but they have a different 360-degrees-rotatable mechanism to control the orientation of their water outflow. The steering grid bends the flow approximately 180° and then exhausts its water flow underneath the hull, whereas the stern thruster bends the flow approximately 90° and then exhausts its water flow through the sides of the hull (except when it is orientated to provide backwards thrust, then the water flow will also be expelled underneath the hull). The magnitude of the thrust force of both thrusters can be controlled by their propeller speed, n. Due to the differences in their steering mechanism design and their propeller size, both thrusters generate different thrust forces at equal propeller speeds, of which more details can be found in [10].

3.2. Onboard Sensors

Two sensors measured the movements of the vessel during the conducted experiments of section 4. A Septentrio AsteRx-U Marine GNSS receiver with two mushroom antennas measured the heading and position of the vessel [13], and a SBG Ekinox-2E IMU/INS provided its yaw-rates [14]. This IMU also measured the reported headings from section 4 based on an internal Kalman filter which received corrections from the GNSS. The main GNSS antenna was placed at the stern of the vessel and reported its own position. The auxiliary antenna was placed 4,44m in front of the main antenna and thus unlocked the access to heading information. The IMU was positioned 95cm in front of the main GNSS antenna.

4. Results and Discussion

This section shows three of the aforementioned manoeuvres for inland vessels which were performed with the Cogge on a lake in Rotselaar (Belgium). The Cogge conducted all these experiments autonomously with no crew on board. The values of the parameters of these tests were empirically chosen. Section 4.1 discusses an ITTC-suggested manoeuvre, namely the Crabbing Test, whereas sections 4.2 and 4.3 respectively handle the here-proposed Counter

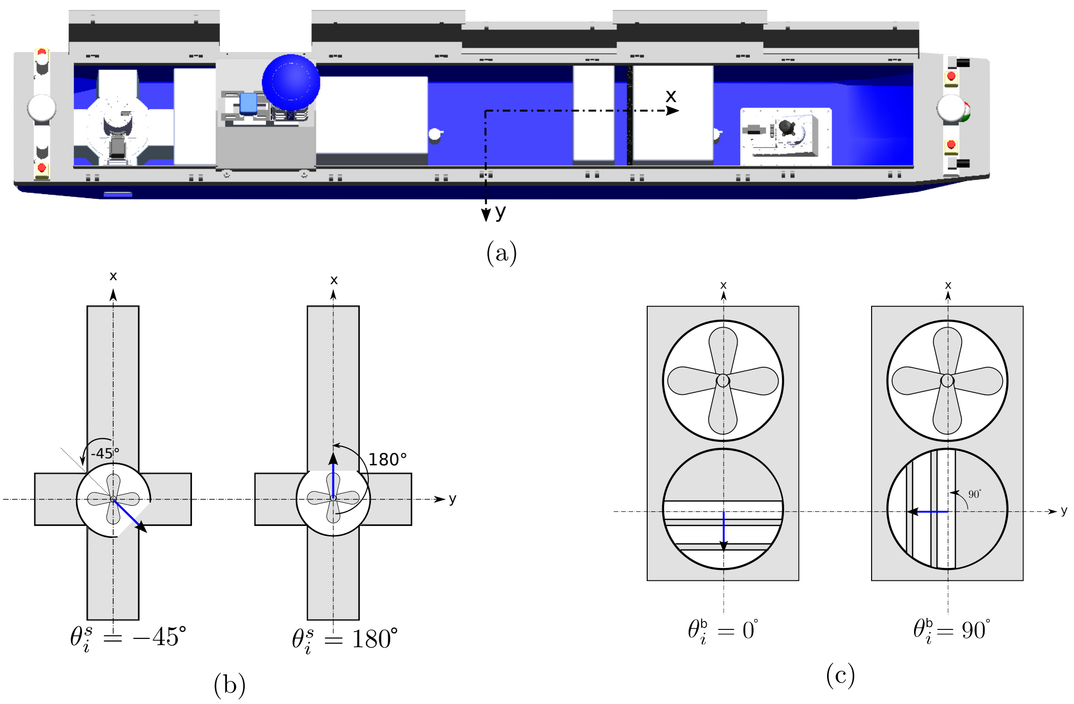


Figure 2: (a) design drawing of the self-propelled scale model barge with its (b) 360-degrees steerable 4-channel thruster at the stern (abstract top view of its bottom section to show the angle convention θ_i^s), and (c) 360-degrees-steerable steering grid thruster in the bow (abstract top view of its bottom section to show the angle convention θ_i^b), adapted from [11, 10].

Thrust and Sine Angle tests. In order to give an idea of the testing conditions, a top view photo of a counter-clockwise Counter Thrust Test can be seen in Figure 3.

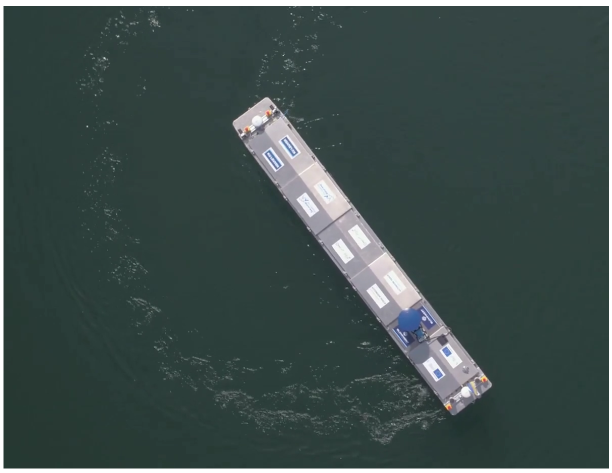
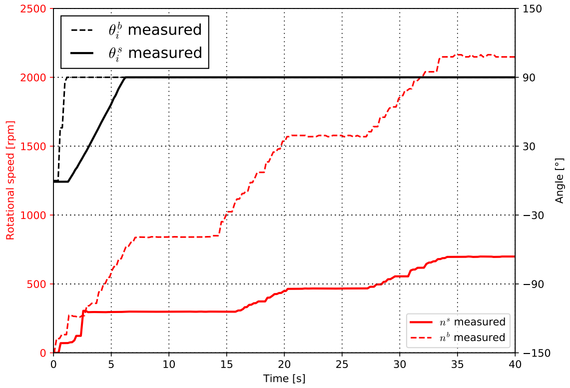


Figure 3: Counter clock-wise manoeuvre with the Cogge on Rotselaar lake, this picture was not taken simultaneously with the shown test data of section 4.2.

4.1. The Crabbing Test

Figure 4a shows all the system states measured during the 40s crabbing manoeuvre, i.e. propeller speeds, n, and internal thruster angles, θ_i. The vessel performed a starboard crabbing manoeuvre with simultaneously changing propeller speeds for the bow and stern thruster. Ideally, both thrust forces exert an equal but opposing torque on the vessel such that the vessel does not rotate. During the experiment, an empirically derived propeller speed ratio was used to achieve this. Figure 4b plots the measured headings (relative to the start heading) and yaw-rates which indicate that the vessel kept a rather straight orientation during the whole manoeuvre. Finally, Figure 4c displays the trajectory the main GNSS mushroom covered.



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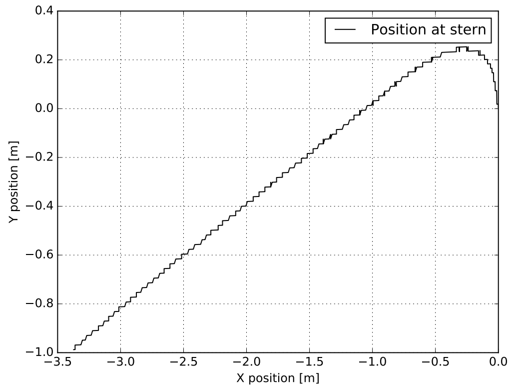

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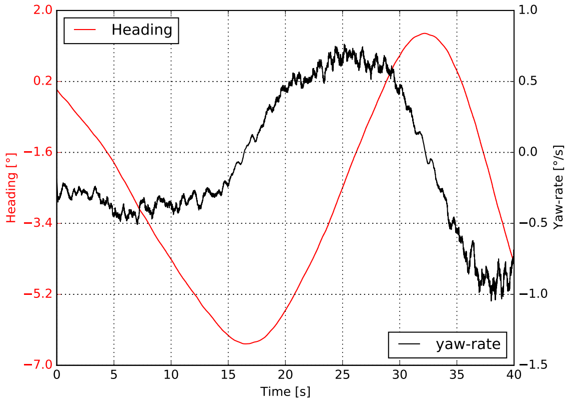
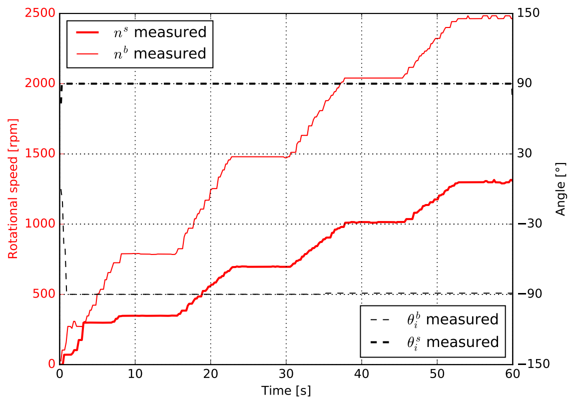


(b)

Figure 4: The Crabbing manoeuvre with (a) $\theta_i^b = \theta_i^s = 90°$, $n^b = 0$ to 2150rpm using a staircase profile, and $n^s = 0$ to 700rpm using a staircase profile, (b) shows the measured headings and yaw-rates, and (c) shows the trajectory of the main GNSS mushroom.

4.2. The Counter Thrust Test

Figure 5a demonstrates the measured system states during the performed counter-clockwise Counter Thrust Test. Here too, a propeller speed ratio was used in order to provide approximately equal thrust magnitudes, similar to section 4.1. As the measured headings of Figure 5b illustrate, the Cogge rotated almost twice over the 60s time span of the manoeuvre. Lastly, Figure 5c exposes that the Cogge did not drift far during the experiment, as the position of the main GNSS mushroom, which is placed at the stern of the 4,8m long vessel, described a spiraled-ellipse shape within a 5m by 5.5m rectangular box. The spiral shape of the GNSS mushroom antenna indicates that there was a small deviation of the starting position which might be caused by: (i) the error on the experimentally tuned propeller speed ratio which could be diminished in the future, and (ii) external disturbances which might have been present.



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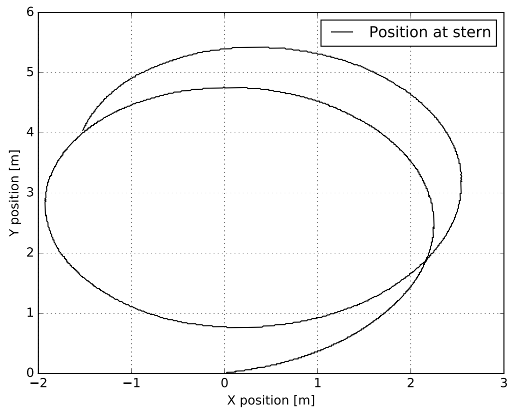

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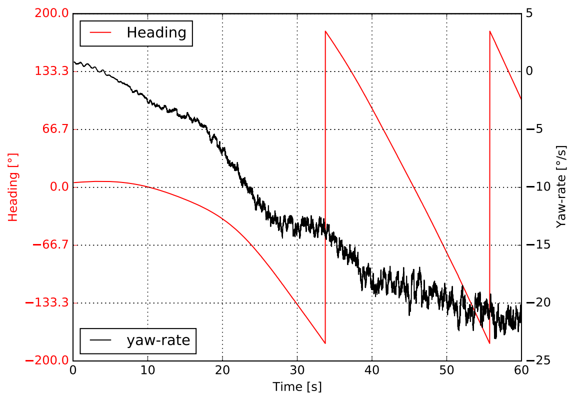
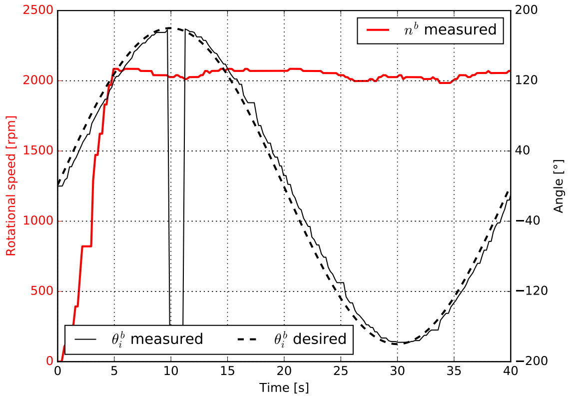


(b)

Figure 5: Counter-Clockwise Counter Thrust manoeuvre with (a) $\theta_i^b = -90°$, $\theta_i^s = 90°$, $n^b = 0$ to 2450rpm using a staircase profile, and $n^s = 0$ to 1300rpm using a staircase profile, (b) shows the measured headings and yaw-rates, and (c) shows the trajectory of the main GNSS mushroom.

4.3. The Sine Angle Test

Figure 6a depicts the measured system states during a Sine Angle Test conducted by the bow thruster, hence the system states for the stern both equalled zero. The bow propeller reached a rotational speed of 2050rpm and the angle of the steering grid oscillated between [-180, 180]° over a period of 40s, which resulted in the measured headings and yaw-rates of Figure 6b. These yaw-rates offer an impression of the achievable turning rates of the vessel at low advance speeds. Evidently, the same manoeuvre could be performed over a longer period, giving the yaw-rates more time to settle, or with higher advance speeds. Finally, Figure 6c portrays the distance covered by the main GNSS mushroom during this experiment.



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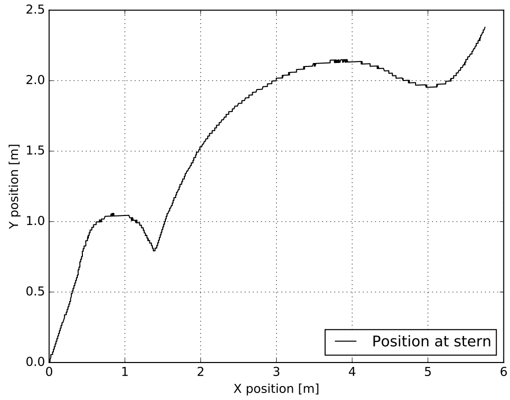

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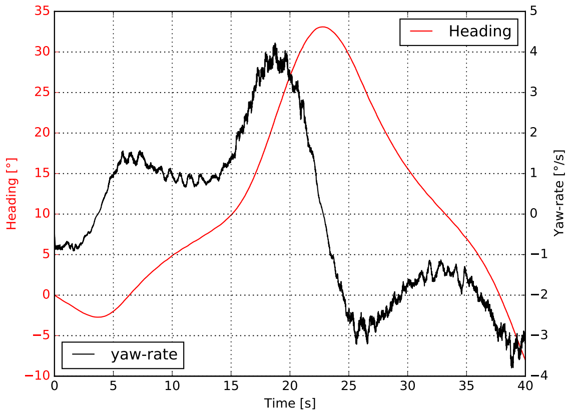

(b)

Figure 6: Sine Angle Test with the bow thruster: (a) θ_i^b oscillating between $= [-180, 180]°$ over 40s, n^b = 2050rpm, θ_i^s = 0°, and n^s = 0rpm, (b) shows the measured headings and yaw-rates, and (c) shows the trajectory of the main GNSS mushroom.

5. Conclusion and Future Work

This paper reviewed the existing standardised test manoeuvres in order to highlight the inland-applicable test manoeuvres as these inland vessels often tend to have non-conventional propulsion systems or an unconventional placement of their actuators. Due to the scarcity of such manoeuvres, this study suggested three additional manoeuvres: (i) the Counter Thrust Test which can judge the turning capabilities of the vessel in spatially restricted areas, (ii) the Sine Angle Test which can uncover a wide range of achievable turning rates, and (iii) the Simultaneous Zigzag Test which can utilise the full capability of the vessel to perform a regular zigzag test. Afterwards, three manoeuvres were conducted with an unmanned autonomous inland cargo vessel: (i) the existing Crabbing Test, (ii) the proposed Counter Thrust Test, and (iii) the suggested Sine Angle Test which was performed with the bow thruster. The successful execution of these manoeuvres provided fruitful insights in the dynamic capabilities of the vessel at hand. For example, the Counter Thrust Test showed how the vessel can locally rotate with little drift. Evidently, the currently performed tests and the list of suggested additional manoeuvres do not exhaust the wide range of possible and useful manoeuvres which are tailored for inland cargo vessels. Consequently, in their future works, the authors aim to define more manoeuvres and their subsequent metrics with an additional focus on the automation potential of the freshly introduced fleet of inland cargo vessels.

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