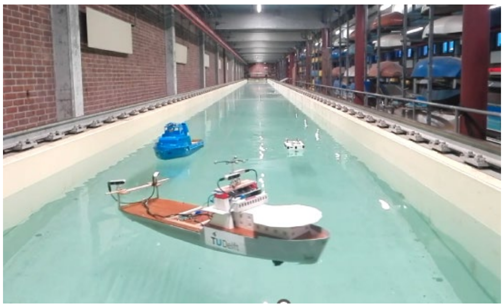

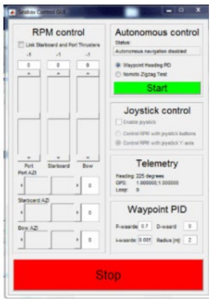

Analysis → Aspects → Scenarios → KPIs → Criteria → Assessment

Development of a strategy for evaluating operational performance and risk for a fleet of urban vessels

Within the framework of the Interreg NSR project AVATAR work package 3

Colophon

- *Report of Development of a strategy for evaluating operational performance and risk for a fleet of urban vessels. Within the framework of the Interreg NSR project AVATAR work package 3*
- Interreg VB: AVATAR
- This document is published within the AVATAR project, an INTERREG project of the North Sea Region programme 2014-2020 as one of the reports for WP4.
- It is allowed to distribute this publication.
- The publication may be cited as: Yusong Pang, Julian Tas, Vittorio Garofano & Rudy Negenborn (2023): Development of a strategy for evaluating operational performance and risk for a fleet of urban vessels, publication in the framework of AVATAR, a project co-funded by the INTERREG North Sea Region programme 2014-2020 (ERDF).
- Source of the photo(s) on the cover: TU Delft.

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Document version:

Version	Date
V1.0	15.08.2022
V2.0	26.07.2023

Project partners AVATAR:

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1 Introduction

1.1. Background

The most used way of transporting freight and passengers in urban areas is by roads. Nowadays, the roads are full of traffic and congestion occurs on daily bases. One way to reduce the stress on the roads in urban areas is to improve inter modal transport. In present day, a large part of the world's population lives near bodies of water with the potential to be used as transport routes. However, the waterways of these urban areas are not extensively used for transport[2]. Urban areas with connecting waterways have the right conditions to use vessels for transport, for example a city with canals close to the public. The development of autonomous surface vessels (ASV) is promising to improve the inter modal transport in these areas. For an vessel to be autonomous it requires a high level of automation, so it is not depended on human controllers. An ASV should be able to operate with environmental data collected by itself. The ASV is lesser heard about than the more popular autonomous vehicle, but nevertheless a lot of progress towards the practical realisation of ASVs is booked. For example in Norway a test site for unmanned vessels is opened in a fjord located in Norway [3], the vessels that are tested in this example can ship both passengers and freight. The designed ASV is versatile in manners of utilization, it can be used to ship passengers across a waterway in places where a bridge would be inefficient, functioning as a ferry. While it also possible that the ASV is used to restock larger vessels, that are not able to moor in harbours for various reasons. With such an versatile vessel it is understandable that the ASV is an interesting technological advancement.

In literature it appears that ASVs can be divided in two groups based on their size and utility, namely the seagoing vessels and smaller vessels for inland waterways. The difference between area of operation brings a lot of different requirements to the ASV design. For example in the MUNIN project [4] a technical concept for the operation of an unmanned dry bulk carrier that operates in the intercontinental trade is developed. The environmental scope of this project focuses only on deep-sea-voyage and not the congested waters of inland waterways. For this research the focus is on the latter group, the use of autonomous vessels in waterways in urban areas, such as city canals. Here, the technology could be used for freight transport and passenger transport. The freight transport could be the restocking of warehouses, shops and restaurants, but could also be applied for delivery directly to costumers. The advantage of the use of autonomous vessels for this purposes is the reduction of traffic on the roads in the urban areas by moving the transport to the waterways. At first, it seems like moving the problem of congestion, but with the technology of autonomous vessels it is possible to create a multi coordinated system of efficient operating vessels. Another large advantage is the reduction of the environmental footprint when using ASVs. This reduction comes in two ways. Firstly by reducing the amount of traffic on the roads, which largely contributes to the production of emissions and secondly, the ASV itself will be fully electric, so is theoretical a zero-emission vehicle [5].

1.2. Gap

The practical use of autonomous vessels on large scale is not something that will be realised in the near future. The technology is mostly still in the experimental phase and also the implementation of fully autonomous vessels conflicts with the regulations. For the autonomous vessel to become legal in public it should be proven functional, safe and reliable. The way to prove these aspects is to validate them by testing. Nowadays, a lot of research is focused on control, trajectory planning, communication and the practical use of autonomous vessels. However, as stated before testing the autonomous vessel is an important factor to get it legally approved. On the subject of testing and assessing the functioning of ASVs such as navigation, trajectory following and collision avoidance limited research is published, when searching through literature no complete testing methods or procedures are found. This literature gap can be exploited and is redefined in the objective of this research.

1.3. Object and scope

The goal of this research is to find the answer for the following question: How to test and asses autonomous vessels in urban areas?
The focus of this research is on developing a testing guideline for autonomous vessels in urban areas, so the control and design of autonomous vessels is out of scope. As stated in the object the focus is on urban areas, so the larger maritime sector is out of scope. Furthermore, the test procedure is designed for three scales that are predetermined for the AVATAR project by Interreg North Sea region [6], however the first output will be a general guideline. With the scope and object of the research defined, the research question that needs to be answered to reach the goal is defined and is the following:

What will a method to test and asses the performance of autonomous vessels using KPIs based on testing scenarios look like?

To find the solution for the main research question multiple sub questions are defined, that by answering will bring the pieces to complete the general testing guideline. To find the answers for the sub question listed below an approach is constructed.

- What European laws and standards should be followed to legally introduce ASVs, what test procedures for ASVs are already available and what test procedures that can be retrieved from conventional vessels are useful for ASVs?
- What aspect criteria should be taken in account?
- What testing scenarios could asses the aspect criteria?
- what is the influence of the operational environment on the testing scenarios?
- What are the objectives for the autonomous vessels to perform in these scenarios?
- What are the KPIs of the test scenarios based on the objectives?
- What parameters and measurement methods should be used to track the KPIs?
- How is the performance of the individual test scenarios assessed?
- How does the application of the general guideline on the AVATAR vessels look like, taken in account the operational environments ?

1.4. Approach

Firstly, the literature will be consulted to find the important aspects that need to be validated by testing and also find possible testing scenarios and environments. Using the findings from the literature study the assessment aspect are defined, they will help assessing the ASVs behaviour and control. Thereafter the scenarios which are executed during the tests are designed. These testing scenarios have objectives that are coupled to the aspects they contribute to. Next up the key performance indicators are described for all testing scenarios. These KPIs are used to asses the performance of the autonomous vessel. The KPIs values are not always directly retrievable via measurements, therefore measurable parameters, that lead to the KPI value, should be determined. After that the measurement methods that are required to collect the parameter data are defined. To assess the performance of the ASV with the KPIs, criteria should be set to judge the performance. With all these pieces the testing method can be designed, this approach is made visible with the flow chart in figure 1.1. After the completion of the general guideline it is adapted to the AVATAR project by defining three scales of vessels used in testing, namely the model scale, semi-full scale and the full scale. Then at last the recommendations for a testing module are given and the whole research is concluded.

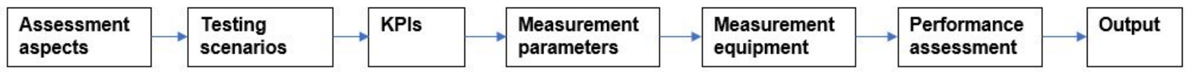

Figure 1.1: Approach for designing the testing guideline

1.5. Report outline

In chapter 2 literature is consulted to find out what aspects are important for autonomous vessels and should be tested, based on vessel behaviour, vessel control, regulation and cooperation of multiple autonomous vessels. The assessment aspect and testing scenarios coming forward from these aspect are described in chapter 3. Then in chapter 4 the objectives of the scenarios are described and the corresponding KPIs are constructed. In chapter 5 the procedures for all the test scenarios are designed including the measurement parameters, measurement methods and for the KPIs to satisfy. At the end of this chapter the finalized general guideline is provided. In chapter 6 the general guideline is adapted to the three scales of AVATAR, based on important aspects and feasibility. In chapter 7 conclusions are made about the design of the testing method and recommendations are made for future improvements of the method.

2

Literature survey

In this section relevant literature to answer the research questions is studied. The goal of the literature survey is to find assessment criteria, testing scenarios and the KPIs that are important for the validation of the autonomous vessels. When searching for literature relevant to this goal, it is noted that testing scenarios are available in different aspect categories. So it is determined that four categories are defined to use in which the scenarios are subdivided. These categories are as follow:

- Manoeuvring
- Path following
- Collision Avoidance
- Vessel collaboration

The literature survey is used to find scenarios and corresponding KPIs for all categories.

2.1. Manoeuvring

First the standard for ship manoeuvrability of the International Maritime Organization (IMO) is consulted [7]. This standard contains multiple manoeuvring test scenarios for conventional vessels and is encouraged to be used for new constructed vessels since 2004. This standard is also applicable for autonomous vessels because the main principle of manoeuvring stays the same. The test maneuvers given in the standard with a brief description of the functionality of the test are as follows [8]:

- *Turning test.* For initial turning and steady turning ability
- *10/10 zigzag test.* For yaw checking ability, course-keeping ability and initial turning/course changing ability
- *20/20 zigzag test.* For yaw checking ability and course-keeping ability
- *Stopping test.* For emergency stopping ability
- *Pull-out test.* For inherent straight-line stability
- *Spiral test.* For inherent straight-line stability

In table 2.1 the list of maneuvers is shown with corresponding KPI and requirement. These requirements are based on the length of the vessel and the velocity during the test.

Table 2.1: IMO standard table for manoeuvring [7]

Measure of Maneuverability	*Criteria and Standard*	*Maneuver*	*IMO Standard*	*ABS Guide Requirement*
Required for Optional Class Notation				
Turning Ability	Tactical Diameter	Turning Circle	$TD < 5L$	Rated $Rtd \geq 1$
	Advance		$Ad < 4.5L$	Not rated $Ad < 4.5L$
Course Changing and Yaw Checking Ability	First Overshoot Angle	10/10 Zig-zag test	$\alpha 10_1 \leq f_{101}(L/V)$	Rated $Rt\alpha_{10} \geq 1$
	Second Overshoot Angle		$\alpha 10_2 < f_{102}(L/V)$	Not rated $\alpha 10_2 < f_{102}(L/V)$
	First Overshoot Angle	20/20 Zig-zag test	$\alpha 20_1 \leq 25$	Rated $Rt\alpha_{20} \geq 1$
Initial Turning Ability	Distance traveled before 10-degrees course change	10/10 Zig-zag test	$\ell_{10} \leq 2.5L$	Rated $Rti \geq 1$
Stopping Ability	Track Reach	Crash stop	$TR < 15L$ (1)	Not rated $TR < 15L$ (1)
	Head Reach		None	Rated $Rts \geq 1$
Recommended, Not Required for Optional Class Notation				
Straight-line Stability and Course Keeping Ability	Residual turning rate	Pull-out test	$r \neq 0$	Not rated $r \neq 0$
	Width of instability (2) loop	Simplified spiral	$\alpha_U \leq f_a(L/V)$	Not rated $\alpha_U \leq f_a(L/V)$

Secondly, some manoeuvring test examples are consulted to show what scenarios are tested and what practicalities are notable. In a Portuguese research [9] an model of a sea going vessel was constructed and tested for its autonomous manoeuvring abilities. During the manoeuvring the model's heading and advance speed is controlled through the rudder positions and propeller rotations. The autonomy level of the vessel reaches to the point where it is able to follow a path of set waypoints by the user. During the test multiple parameters were measured, with the most relevant and important being: the geographical coordinates, surge and sway velocities, roll and pitch angles, heading angle and yaw rate. Also some environmental parameters were taken in account such as the relative wind speed and direction. All these parameters with the help of a kinematic model contributed to determining the performance of the autonomous manoeuvrability of the model. The test setup to perform trajectories autonomously included the predetermined waypoints, an estimation of the parameters over time according to the kinematic model with disturbances included and the measured parameters. In the end it was concluded that the manoeuvring test were performed successfully since the measured values corresponded to the estimated values with only small deviations, it should be noted that these tests were performed on a calm lake with perfect weather conditions.
From the same Portuguese research as mentioned in the previously [9] it is noticed that repetition of the tests with different trajectories and speeds is important to validate the control, guidance and navigation systems of an ASV.

2.2. Path following

In the study [10] an ASV is developed on a catamaran to validate fundamental navigation technologies, such as waypoint tracking and obstacle avoidance. The performance tests that were executed included the measurement of the maximum speed and the turn radius of the ASV. The tests described in the study [10], which is already mentioned in the last section, includes waypoint tracking and obstacle avoidance. To test the performance of the waypoint tracking an acceptance radius around each waypoint was set, so the errors could be objectified.

2.3. Collision avoidance

There are regulations for collision avoidance regarding vessels, namely: COLREG International Regulation for Preventing Collisions at sea [11]. The question does arise whether the COLREG regulation is still relevant for autonomous vessels, since these regulations originate from 1972. According to Maritime Executive [12] the causes of most collisions can be broken down into two broad categories:

- Failure to maintain a proper look-out.
- Failure to take the appropriate avoiding action.

The manual look-out of the conventional vessel is replaced by sensors on the ASVs. When sensor failure detection and redundant sensors are available this category should be covered. Also it expected that ASVs can include the COLREG rules into the decision making algorithm, so this category is also covered. The COLREGs are still fit for purpose when dealing with autonomous vessels, it will only require some amendments regarding the sensors and algorithms. In this regulation mainly three situations are described. The first situation is overtaking, any vessel overtaking any other shall keep out of the way of the vessel being overtaken. Secondly a head-on situation, in this case two power-driven vessels are meeting on reciprocal or nearly reciprocal courses and the following action is that each vessel shall alter her course to starboard, so that each shall pass on the port side of the other. The last situation is a crossing situation. When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel. These are scenarios that should be included in the testing guideline for ASVs.
In literature experiments are described to test aspects of collision avoidance, these experiments can be used to form testing scenarios for the guideline. It can be busy on with vessels on inland waterways, so it is realistic that multiple COLREG situations occur at the same moment. In the study [13] experiments are done with consecutive COLREG situations. Also this paper uses the velocity obstacles approach for moving hazard avoidance. Velocity obstacle approaches generate a cone shape obstacle in the velocity space and ensure that there will be no collisions as long as the ASVs velocity vector is outside the velocity obstacle. This study extend velocity obstacles in the context of maritime navigation subject to COLREGS, namely velocity obstacles is used to avoid moving and static hazards, however it also generates an additional set of constraints in the velocity space when the ASV is in certain COLREG situations. In figure 2.1 and 2.2 a scenario with a series of consecutive COLREGs maneuvers is displayed. In this scenario the ASV is going head-on-head with two vessels and when it makes an evasive maneuver it goes head on with a vessel that original was on an crossing path.

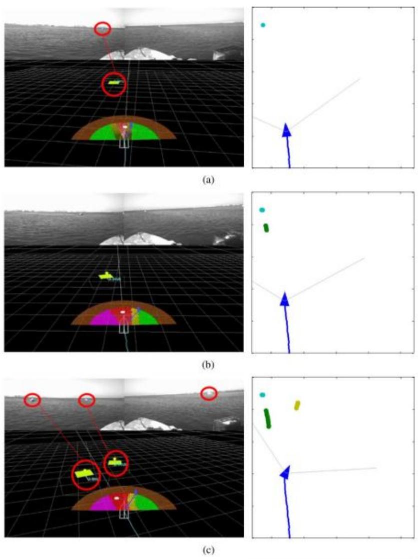

Figure 2.1: Scenario of four boat COLREGS runs: Overtaking and head-to-head; (a) ASV detects a contact; (b) ASV recognizes a head-on situation; (c) ASV detects another vessel in the head-on situation

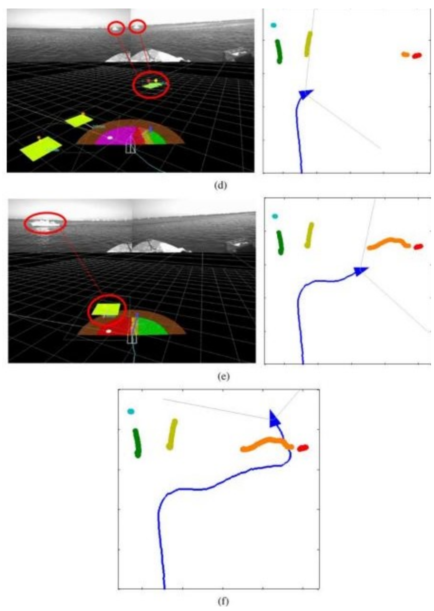

Figure 2.2: (d) ASV detects a crossing vessel; (e) ASV avoiding the crossing vessel; (f) ASV's overall path after a series of COLREGS maneuvers.

The collision avoidance ability of autonomous vessels is discussed in the study [14]. The parameters used for manoeuvring also correspond to collision avoidance, the main difference is that if collision with different vessels is a probability then communication between the agents is important. Here it is also noted that there is a trade-off between collision avoidance and track-keeping, since a change of course costs extra time and resources to finish the journey. The costs can be reduced by having communication between both vessels to minimize the course change of both and still avoid collision. To validate the feasibility of the collision avoidance system in the study [10], an object was placed on the course of the ASV to check whether the system could detect the object and foresee the collision path. If the probability of collision with the object reached a set threshold, then the ASV would make an evasive manoeuvre.

2.4. Vessel collaboration

No regulations are found to derive fleet scenarios from. Instead there is searched for research about the use of autonomous vessel in clusters. In a research where a fleet of kayaks is used to guard a specific location and can be used as a blockade, a collaborative control architecture is described [15]. This collaborative control uses a cluster space to manage the relative locations of the vessels in the fleet, this is shown in figure 2.3. The goal of the research is to use a fleet of robotic vessels capable of guarding critical assets from threats. This guarding requires a strict formation. The experiments in this study were performed successfully and are relevant for the design of the guideline, since fleet formations should be included as scenario.

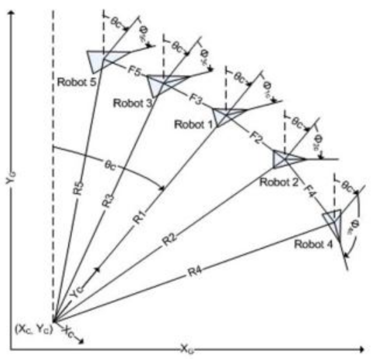

Figure 2.3: Cluster space of five ASVs [15]

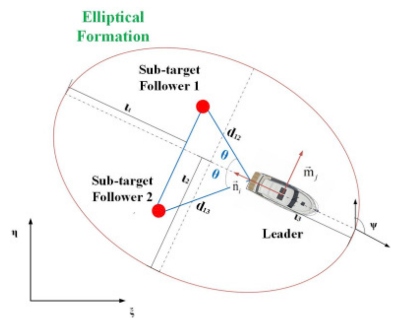

Figure 2.4: Scheme of ASV formation [16]

In the study [16] a system for motion-planning, collision avoidance, guidance and control of an ASV formation is presented. The ASV formation used in this study has an elliptical shape with a leader-follower architecture that contains a leader and two following vessels, see figure 2.4. An cooperative motion planning unit is designed to compute the desired path for the leader and followers ASVs formation using marine environment, grid map, static and dynamic obstacle information. In this unit the formation shape is pre-defined based on the number of ASVs, distance between the ASVs and the formation angle. In this formulation the leader target point is defined as the ASV formation target and is unaltered during the task, while the followers desired target position is recomputed during each time step according to follower-leader formation shape. In the study it is noted that during some situations the shape of the formation has to change to minimize the risk of hazardous situations.

2.5. Conclusion of literature survey

The available literature is used to determine the testing scenarios based on regulations and on experiments. The corresponding KPIs of each of these found scenarios are described. While also the other way around occurs, namely important KPIs are found in literature and the scenarios are designed to measure these KPIs. Coming forward from the literature survey is that the important aspects for ASVs are mostly related to maneuvering, path tracking, collision avoidance and vessel collaboration. These skills are used as categories in the rest of the study. It is worth noting that a sufficient testing method for ASVs includes repetitions of different experiments.

3 Testing Scenarios

In this chapter the scenarios and their objectives that will be included in the test method are described. Firstly, the assessment aspects are determined. After that the scenarios are designed and coupled to the relevant aspects. In the scenarios description the limits of the environment are also discussed. At last an overview of the scenarios with corresponding assessment aspect are given.

3.1. Assessment aspects

The overall performance of the ASV can be determined by the validating different aspects and determining which of these aspects are more relevant to the purpose of the ASV. For a vessel to become versatile is should have good performance on most aspects. The assessment aspects are derived from factors such as economical factors, energy consumption, maneuverability, safety, reliability and control. The assessment aspects can be rated by multiple scenarios, while also multiple aspects can be rated by one scenario. So the performance of an aspect is dependent on multiple scenarios and one scenario could also contribute more to the overall performance of the ASV through this dependency. The aspects that are considered in this study are shown in table 3.1.

Table 3.1: The assessment aspects

Safety	Navigability	Turning ability	Straight line stability
yaw checking ability	Course keeping ability	Stopping ability	Control
Cost-efficiency	Energy-efficiency	Redundancy	Reliability

3.2. Scenarios

The objective of this research is to design a testing method, which should be applicable to multiple type of inland waterway ASVs with some minor adjustments. From the literature survey multiple aspect came forward, which will contribute to forming the testing scenarios. In this section the testing scenarios and the assessment aspect they relate to are described. Firstly, the basic functionality of the vessels such as the ability to maneuver should be tested, with these test the vessel behaviour is tested. Secondly, the main challenges for autonomous surface vessels is the capability to follow a path, manoeuvring and avoiding collisions. The testing scenarios should be based on that. Moreover an interesting development that is applicable to autonomous vessels is the multi-agent control. Testing scenarios that include multiple collaborating ASVs should be designed to asses the performance of this application. The testing scenarios should be designed in such a way that the testing can be repetitive. The testing scenarios will be put in four categories that are defined in the literature survey:

- Manoeuvring
- Path following
- Collision avoidance
- Multiple vessels

3.2.1. Manoeuvring

In this category the manoeuvring functions of the autonomous vessel are subjected to basic tests, where the performance of the ASV can be assessed. The performance of the ASV in this category should be up to a standard level, otherwise it is futile to perform the tests of the other categories. Also, the control of the rudder and propulsion will be tested to see if the response of the vessel will be accordingly. Based on these functions the scenarios are set. In the literature review 2 the standard for ship manoeuvrability from the IMO is mentioned. In this standard there guidelines that describes tests for manoeuvring abilities of conventional vessels. An ASV should have those same abilities, so these guidelines are also applicable to ASVs and are used as scenarios.

Navigate in a straight line

The first scenario is to check the ability of the ASV to move straight forward. This should first be done in a calm environment. This test contributes to mapping the vessel behaviour and to see whether the ASV is stable on straight paths. The stability of the vessel when it travels straight is important to the following aspects:

Control	*The propulsion and rudder should function with the control.*
Course keeping ability	*The ASV has to stay on course.*
Navigability	*The navigation in straight line contributes to the total navigability of the ASV.*
Reliability	*A good straight line navigation performance contributes to the overall reliability of the ASV.*

Mooring test

In this scenario it is checked whether the ASV is capable of stopping at an exact location. This is useful since the ASVs in urban environment should be able to stop autonomously at given destinations, where it is able to moor. Overshooting or undershooting the mooring location can result in dangerous situations or led to extra actions. Therefore is the grade of the performance an influence for the following aspects:

Control	*To let the ASV stop at the exact destination requires good control.*
Cost and energy efficiency	*Repositioning at the exact location requires extra actions.*
Navigability	*Reaching the exact destination contributes to good navigability.*
Safety	*Overshooting the mooring location can result in dangerous situations.*

Reach maximum speed

In the design stage of an ASV one of the design points is the expected speed the ASV would have. In this scenario the vessel should also move in a straight line, only now with maximum power to reach its maximum speed. The knowledge of the maximum reachable speed of the ASV contributes to mapping of the vessel behaviour. This scenario can be expanded by testing the energy consumption over different speeds of the ASV in the same environment. The aspects this scenario is relevant for are the following:

Energy efficiency	*The range of speeds and corresponding energy consumption gives insight in energy efficiency.*
Navigability	*The maximum speed influences maximum turning radius and therefore the overall navigability.*

Stopping test

In this scenario the objective is to measure the stopping ability of the ASV in a stop engine-full astern maneuver. This maneuver is performed after a steady approach and ends when the vessel starts going backwards. This maneuver is normally used to check the maximum stopping distance, which is important to determine with respect to safety. It is important to note that this test scenario can only be performed at ASVs that have the ability to go backwards. The assessment aspect this scenario contributes to are the following:

Control	*The maneuver requires going backwards which needs to be controlled*
Reliability	*When the stopping distance is know and included in the control the ASV has a smaller change on collisions*
Safety	*The knowledge of the stopping distance in case of emergency contributes to the overall safety.*
Stopping ability	*When the scenario is performed with an range of speeds the stopping ability of the ASV is mapped.*

Turning test

The U-turn is useful when changing destination or when the vessel is leaving a berthing situation. This scenario is used to determine the minimal turning radius of the ASV. This will depend on the speed the experiment is executed with. The knowledge of the turning radius in a range of different speeds helps determining whether it is possible to turn in a certain waterway and the navigability of the ASV. This turning radius is gained by performing a turning circle maneuver to both starboard and port. The scenario requires the a relatively large space to perform the turning maneuver. This testing scenario is important for multiple aspects:

Control	*The control of the rudder is tested with scenario.*
Navigability	*The knowledge of the turning radius and advance contributes to the overall navigability of the ASV.*
Turning ability	*Performing this maneuver at a range of speeds maps the initial turning and steady turning ability.*
Yaw checking ability	*The yaw rate of the ASV during this scenario should be checked and limited to a safe value.*

10°- 10°Zigzag

The scenario of so called zigzagging means that the vessel is going to follow a path that looks like saw teeth. From a neutral start the rudder position is set to a certain angular position and when the heading matches this angle, the rudder is set to the negative equivalent of this angular position. This forces the vessels to make the zigzag maneuver and gives insight to the vessels behaviour. The angles of the turns the vessel has to make can differ, but it is reasonable and useful to have angles between 10 to 30 degrees according to [17]. Two zigzag degrees are included in the IMO standard [7], namely the 10 and 20 degree zigzag. The 10 degree zigzag is relevant to the following assessment aspects:

Yaw checking ability	*The heading overshoot reached before the yawing is being cancelled out by the counter-rudder determines the yaw checking ability.*
Control	*The rudder position should be measured to determine the rudder response*
Navigability	*The knowledge of the heading overshoot contributes to the overall Navigability of the ASV.*
Turning ability	*The response time it take to change heading defines the turning ability.*

20°- 20°Zigzag

This scenario is similar to the 10 degree zigzag scenario, it only has a larger turning angle. In this case the rudder is set to 20 degree on both sides. The assessment aspect are also equal to the ones in the 10 degree zigzag except for the turning ability, this is because the rudder angle is less used in normal manoeuvring.

Pull-out test

The pull-out test is an option to determine whether a vessel is dynamically stable and able to keep course. It is performed after the turning circle test. After the completion of this test the rudder should be returned to the neutral position (zero degrees) and kept there until a steady turning rate is obtained. If this turning rate will decrease to zero the vessel is dynamically stable. This scenario contributes to the following assessment aspects:

Straight line stability	*The residual rate of turn determines the stability of the ASV.*
Control	*The rudder should return to the neutral position as smooth as possible.*
Course keeping ability	*The course keeping ability is depending on the straight line stability.*

3.2.2. Path following

This category is relevant to test and asses the navigating skills of the autonomous vessel. The main functioning of ASVs is to reach its destination autonomous. This can be done by giving the ASV its final destination and let it determine the best path, but another option is to provide a set of waypoints for the ASV to follow. The latter one has multiple examples in literature and gives the possibility to influence the optimal route calculated by the ASV. In these case the ASV has to pass all the waypoints to reach its destination along a certain path. The experiments for path following were most of times combined with manoeuvring tests by setting the waypoints under a angle with the next waypoint and measure the overshoot of the turns.
The testing scenario in this category includes path tracking through waypoints. To validate this ability of the ASV the scenario should be performed with different sets of waypoints. These set can differ in relative angles and distances between waypoints. The significant assessment aspects considered with this scenario and the reasoning for using them are described below.

Control	*The accuracy by which the ASV passes the waypoints relies on the control and vessel behaviour.*
Cost efficiency	*Minimal deviation from the optimal path ensures minimal travelling costs.*
Navigability	*Tuning the waypoints in different patterns explores the navigability of the ASV.*
Reliability	*Successfully passing more sets of waypoints increases the reliability of the ASV in path following.*

3.2.3. Collision avoidance

This category includes scenarios that aim to avoid collisions with other vessels or objects. These vessels and objects can be both stationary and moving. Urban waterways usually are busy places where encounters with vessels and other objects are inevitable, so a reliable collision avoidance system is essential for ASVs. A well functioning collision avoidance system will increase the safety of ASVs operating in public. An other important attribute of collision avoidance is the cost in manners of time and energy to avoid objects by changing the set path. As stated in the literature review there are collision regulations set by the IMO. COLREG describes a set op possible encountering situations between two vessels and the sequence or direction in which the vessels should pass, see figure 3.1. An ASV should meet up these regulations as it will participate in public water traffic.

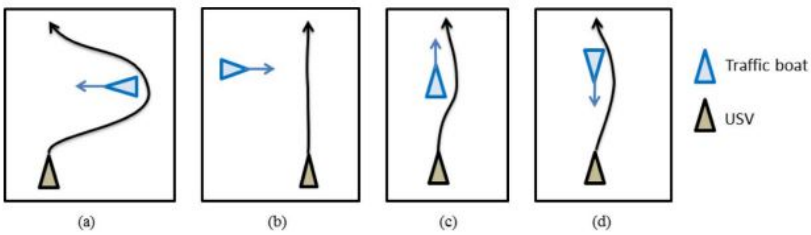

Figure 3.1: Maneuvers required for various COLREGS situations, (a) Crossing from starboard, (b) Crossing from port (c) Overtaking (d) Head-on [13]

Avoid stationary obstacle

In this scenario a stationary obstacle is placed in the test location on the path of the ASV. The purpose of this test scenario is to check whether the ASV registers the obstacle and takes action by changing its heading and decelerating or by stopping fully. The motivation for performing this test is to check the response of the ASV to a possible dangerous situation. The actions taken to evade the obstacle will cost extra energy and time in comparison with the original route and should therefore be limited. The assessments aspects relevant to this scenario are described below including a motivation.

Control	*The registration of the obstacle has to induce an evasive maneuver that is feasible.*
Cost efficiency	*The evasive maneuver should be as smooth as possible by reducing the amount of actions taken.*
Reliability	*Performing tests with different types of obstacles to recognise will contribute to the reliability of the collision avoidance system.*
Safety	*Detecting and avoiding obstacles autonomously will increase the safety of the ASV and the environment.*

Overtaking

In this scenario an extra vessels is necessary, with the same course as the ASV performing the test but with a lower cruising speeds. The vessel behind is the ASV and should have the higher speed. The object is to have the following ASV overtake the vessel in front, while maintaining a certain speed and a safe relative distance. This scenario is shown in figure 3.1(c). According to COLREG it is allowed to pass the vessel in front on both sides, but it is common practice to pass the vessel ahead on its starboard side. The ability to overtake other vessels is important to be more time efficient, since the ASV can remain its optimal speed. The assessment aspect with corresponding motivation are shown below.

Control	*Successfully registering a vessel in front on the same course, determining it has a lower speed and then starting an overtaking maneuver if achievable depends all on the control of the ASV.*
Cost efficiency	*The overtaking maneuver should be as smooth as possible by reducing the amount of actions taken.*
Reliability	*More test in different environments to recognise whether safe overtaking is achievable will add to the reliability of the system.*
Safety	*Determining the amount of space for performing an overtake autonomously will increase the safety of the ASV and its environment.*

Avoid crossing obstacle

The most common crossing obstacle would be another vessel. This scenario is used to check the ability of the ASV to register a moving obstacle and predict the collision path, to see if action is needed to avoid this path. In this scenario there are two possible options; the crossing vessel can be on the port side or on the starboard side. According to COLREG the vessel that has the other vessel on its starboard-side should give-way, see figure 3.1(a)(b). The reason to include this scenario is to determine whether the response and control of the ASV is correct regarding safety. Also if an evasive maneuver is obligatory, this should be done with cost efficiency is mind. To perform the scenario a second vessel that is controllable is required. The assessment aspects that are relevant to this scenario are the following:

Control	*The registration of the crossing vessel has to induce an evasive maneuver that is feasible.*
Cost efficiency	*The evasive maneuver should be as smooth as possible by reducing the amount of actions taken and should only be performed if the ASV has to give way.*
Reliability	*Successfully performing more tests with the crossing vessel approaching from different directions will add to the reliability of the system.*
Safety	*Autonomously detecting and correct decision making when encountering crossing vessels will increase the safety of the ASV and its environment.*

Avoid head-to-head collision

This scenario is comparable to the last, with the main difference that the other vessel is heading towards the target ASV. In this situation the possibility exists that the two vessel can pass each other without the necessity of a course change. This scenario therefore tests the quality of the registration of the moving obstacle and the successive decision making process. If the situation is such that the other vessel is on the ASVs course, COLREG states that both vessel should alter there course toward starboard, so they pass on safe distance, see figure 3.1(d). However the ASV can not assume that the other vessels will dodge it. The performance of this testing scenario gives insight in the following assessment aspects:

Control	*The registration of the collision path has to induce an evasive maneuver that is feasible.*
Cost efficiency	*The evasive maneuver should be as smooth as possible by reducing the amount of actions taken.*
Reliability	*Successfully performing more test in different environments and within a range of speeds will add to the reliability of the system.*
Safety	*Detecting, valuing and avoiding obstacles autonomously will increase the safety of the ASV and its environment.*

Avoid shallow

This scenario is designed to check the depth awareness of the ASV and is important to the safety and reliability of the vessel. The risk of stranding on a sandbank, shallow waters or an underwater obstacle should be taken in account for all vessels. For an autonomous vessel the stranding risk can be decreased with the use of depth measurements, knowledge of the fairway and good decision making. The assessment aspect relevant for this scenario are described below.

Control	*The registration of the underwater obstacle or shallow has to induce an evasive maneuver that is feasible.*
Cost efficiency	*Take knowledge of the depth in fairways in account when determining the optimal route.*
Reliability	*Successfully performing more test with different types of underwater obstacles and depths to register will add to the reliability of the system.*
Safety	*Detecting and avoiding underwater obstacles and shallow waters autonomously will increase the safety of the ASV and its environment.*

3.2.4. Vessel collaboration

This category consist of scenarios that include the use of an autonomous fleet of vessels. The use of fleet formations with multiple ASVs is advantageous for energy consumption and controlling cost, since the the following vessels could use the wake of the leading vessel and the following vessels can use the control outputs of the leading vessel. The scenarios described here are based on the collaboration of the vessels in the fleet and their relative positions. For this guideline a triangular fleet formation with 3 ASVs is considered. For scenarios with more ASVs and different formations the relative positions should be determined and used to asses the fleet performance.

Keep constant distance

In this scenario the object is for the following vessel in a series of two ASV to keep a constant distance to the leading vessel. The following ASV should be able to register the distance to the leading vessel and adjust its speed to keep it constant. This is the basic ability to form a fleet. The assessment aspects the performance of this test contributes to are described below.

Control	*The following ASV has to follow the leading ASV its path and control its speed to remain at a constant distance.*
Navigability	*Keeping a constant distance while travelling a path gives insight in fleet navigability.*
Safety	*Maintaining a minimum distance between the ASVs is important for safety.*

Form a fleet and Keep formation

In this scenario at least three vessels are needed to form a fleet in a certain formation. This fleet formation can be advantageous for fuel consumption, while also less computing power is required by the following ASVs. Another benefit of travelling in fleet formation is less separate ASV have to be supervised. In this formation the vessels should keep a constant relative position to one and another. The formation should hold when the leading ASV is commanded to travel a route. The assessment aspect relevant for this care are described below.

Control	*The control of the systems is responsible for maintaining the relative positions while travelling along path.*
Cost and energy efficiency	*Using different fleet formation can give insight in the energy saved.*
Navigability	*The performance of the fleet travelling a set of paths gives insight of the navigability of the ASVs in fleet formation.*

Change position in formation

For this scenario again a fleet should be formed in a formation, only now the object is for two vessels to switch position in the formation and regain the constant distance to one another. This change of position should be performed while keeping a safe distance. The change of position can beneficial when the environment changes or as redundancy for the leading ASV, so another ASV can take its role. For now only the change of position in the same formation is considered, but it is worth to expand this scenarios in the change of formation of the fleet. This could be temporary so the fleet can pass an obstacle or permanent when the fleet gets to a environment with less space. The assessment aspects relevant to this scenario are the following:

Control	*Changing positions in the formation while travelling a route requires advanced control systems.*
Energy efficiency	*The changing position maneuver should cost minimal extra energy and the optimal route should be maintained.*
Navigability	*When the fleet is capable of adapting its formation so it can navigates it surroundings it adds to the overall navigability of the fleet.*
Redundancy	*The possibility to change the leading ASV adds redundancy to fleet operations.*
Safety	*Changing positions while following a route brings extra risk of collision between the fleet ASVs, maintaining a safe distance contributes to safety.*

3.2.5. Overview of the scenarios

In this subsection an overview of all the scenarios that are included in the guideline is given. In table 3.2 the objectives and the corresponding assessment aspects are given. This gives an overview why the scenario is included to the testing method.

Table 3.2: All testing scenarios with corresponding objective and assessment aspects

Scenario	Objective	Assessment Aspects
Navigate in straight line	Determine course stability on straight line	Control; Course keeping ability; Navigability; Reliability
Mooring test	To stop at exact location	Control; Cost and energy efficiency; Navigability; Safety
Reach maximum speed	Determine max speed and optimal speed	Energy efficiency; Navigability
Stopping test	Determine emergency stop distance	Control; Reliability; Safety; Stopping ability
Turning test	Determine turning ability	Control; Navigability; Turning ability; Yaw checking ability
10-10 zigzag	Determine initial turning and yaw checking ability	Yaw checking ability; Control; Navigability; Turning ability
20-20 zigzag	Determine initial turning and yaw checking ability	Yaw checking ability; Control; Navigability; Turning ability
pull-out test	Determine course keeping stability	Control; Course keeping ability; Navigability; Straight line stability
Path following	Determine the path following ability and efficiency	Control; Cost efficiency; Navigability; Reliability
Avoid stationary obstacle	Determine the response to unsafe situation	Control; Cost efficiency; Reliability; Safety
Overtaking	Overtake slower vessel in safe manner	Control; Cost efficiency; Reliability; Safety
Avoid crossing obstacle	Registration of situation, use regulations and take action accordingly	Control; Cost efficiency; Reliability; Safety
Avoid head-to-head collision	Registration of situation, use regulations and take action accordingly	Control; Cost efficiency; Reliability; Safety
Avoid shallow	Registration of situation and avoid getting stuck	Control; Cost efficiency; Reliability; Safety
Keep constant distance	Follow the leading ASV with constant distance	Control;Navigability; safety
Form a fleet and keep formation	Follow the leading ASV and keep relative position within the fleet	Control; Cost and energy efficiency; Navigability
Change position in formation	Change formation position of the ASVs to adapt to its environment	Control; Energy efficiency; Navigability; Redundancy; Safety

3.3. Environment

The scenarios are performed in a certain environment. The scope of this research are urban waterways, this means that generally there is a limited space to perform maneuvers. When choosing what scenarios from the general guideline are added to a testing procedure it necessary to take in account what environment is available. Scenarios that requires the ASV to make large turns require a lot of space and can no be performed in small waterways. The scenarios from the collision avoidance and fleet collaboration categories require obstacles or extra vessels and are therefore also limited by the available space.

Another aspect connected to the environment are environmental forces acting on the vessel which should be taken in account when determining the vessel behaviour. A lot of wind from one side can make the vessel drift and give faulty results when not measured and considered. For the same reasons also the flow velocity of the waterway should be considered, when calculating the results.

4

Key Performance Indicators

To design a testing method it is necessary to know what performances should be tracked. In the previous chapter the test scenarios and their objectives are described and the motivation for selection of these scenarios is given. In this chapter the key performance indicators (KPIs) for each scenario are determined. These KPIs are determined based on the objective of the test scenario. Firstly, the dynamic model of a vessel will be defined, since this is used to estimate the measured parameters and give an important insight in the set KPIs.

4.1. Dynamic model

Figure 4.1 shows a dynamic model of a vessel with 6 degrees of freedom [18]. The three motions along the x-, y- and z-axis are respectively called surge, sway and heave. The three rotations about the x-, y- and z-axis are respectively called roll, pitch and yaw. For surface vessels the heave, pitch and roll are for most dynamic models neglected since it is assumed that these motion variables are small. Additionally to the dynamic model the mathematical model of the non-linear dynamics of vessels can be found in literature. This can be important to run numerical simulations of some of the described tests, but is considered out of scope for this research. The coordinate system shown in this dynamic model is body fixed. For the calculation of the KPIs the body fixed coordinates system along with the global coordinates are used, depending on convenience.

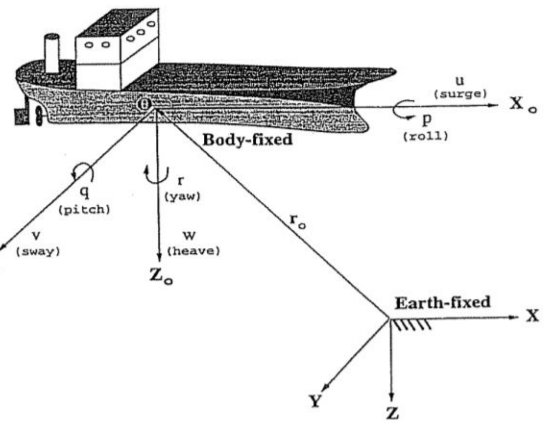

Figure 4.1: Dynamic model of a vessel

4.2. Manoeuvring KPIs

The KPIs in this category are based on the objective of the test scenario and includes aspects as the turning angle and the angle overshoot and are mostly relevant to determine the vessel behaviour.

Navigate in a straight line

Firstly, for navigating in a straight line the objective is to minimize the deviation from this line during the test. This deviation can be measured in length units and be used as the KPI in this scenario. What deviation from the straight line is allowable to call it a good performance is depends on the requirements and size of the ASV. The best way to describe the performance threshold for all scales is to use a ratio of the ship length. To make an good estimate of the deviation of the course the KPI is the is separated in two parts, namely the average and the extreme deviation.

Mooring test

For this scenario the objective is to stop at a designated location, hereby it is important to minimize the deviation of the exact stopping location with respect to the set stop location. It is possible to have some overshoot or to stop too early. The magnitude of the said deviation is the indicator for the performance of this testing scenario and is the KPI of this testing scenario. The threshold of the KPI should depend on the size of the vessel.

Reach maximum speed

The KPI for this scenario is straight forward, since the objective of the test to reach the maximum speed of the vessel, the maximum speed is also the KPI. The performance can be measured by comparing the maximum speed from the test to the expected maximum speed of the vessel. This scenario can be expanded by tracking the energy consumption over the entire speed range, so the optimal cruising speed can be determined.

Stopping test

The objective of this scenario is to determine the stopping ability. The stopping ability is measured by the track reach and head reach, see figure 4.2. The track reach is the distance along the track that the ASV covers from the moment the full-astern command is given until the moment it starts moving in opposite direction. The head reach is the distance along the original course of the ASV at the moment of the start of the test. The head reach is measured in the same time range as track reach. According to IMO requirements [7] the track reach should be smaller than 15 ship lengths. It should be noted that this standard is for seagoing vessels and that an ASV used in inland waterways should aim for a smaller track reach.

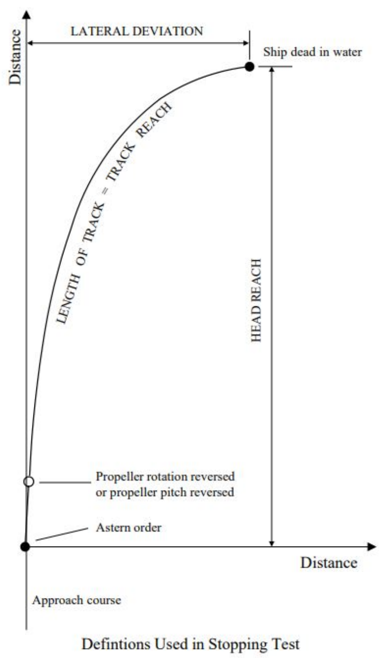

Figure 4.2: Schematic stopping test [8]

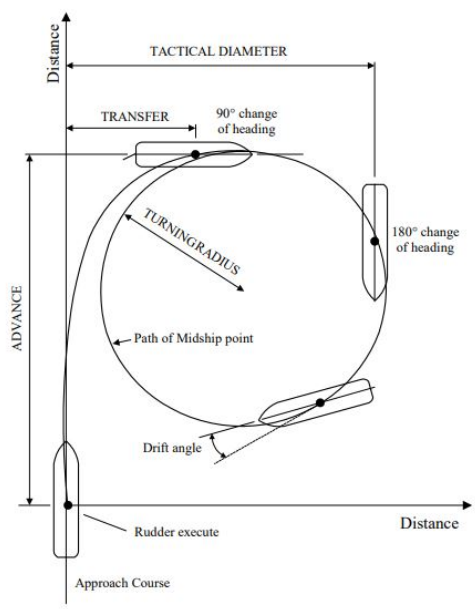

Figure 4.3: Schematic turning test [8]

Turning test

The objective of the turning test is to determine the turning ability of the ASV. The turning ability is defined as the ability to turn the vessel using a maximal rudder angle permissible by the design at given speed, but is required to not exceed more than 35 degrees [8]. The turning ability is determined by performing and measuring the minimum transfer distance to change the heading by 90 degrees and the transfer at 180 degrees change of heading, this is also called the tactical diameter, see figure 4.3. At the start of the turning circle the approach should be steady and the yaw rate should be zero. The KPIs in this test scenario are the transfer distance, the tactical diameter and the advance. The advance is the distance covered on the original approach course from the moment the maneuver starts until the heading of the ASV has changed 90 degrees. According to the IMO standard [7] it is required that the tactical diameter is less than 5 ship lengths and the advance less than 4.5 ship lengths.

10°- 10°Zigzag

During this testing scenario the ASV has to make fast turns by setting the rudder to a constant angle, when the heading angle is the same as the rudder angle, then the rudder is set to the same angle in the opposite direction. The maneuver is shown in figure 4.4. The expectation is that there will be a lag in the response of the heading angle in comparison with the change in rudder angle. This lag creates an overshoot during the turns. Mainly in the first turn the overshoot angle is significant according to a review on the IMO standards [19]. Here is stated that in 10°-10°zigzag the first and second overshoot angle are significant parameters and in a 20°-20°zigzag only the first overshoot angle is relevant. This test is useful to check the initial turning ability and the yaw-checking ability of the ASV. The initial turning ability is defined by the change of heading response. This can be expressed in term of heading deviation per unit distance covered. The yaw-checking ability is a measure of response to counter rudder applied in a certain state of turning, in this case the heading overshoot reached before the yawing tendency has been cancelled out by the counter rudder during the zigzag maneuver. The zigzag maneuver should be initiated to both starboard and port from a initially straight approach. The initial turning ability of the vessel also depends on the magnitude of the first overshoot distance and according to IMO should be not greater than 2.5 ship lengths. Therefore the travelled distance during the first overshoot is the third KPI that should be tracked to asses the performance.

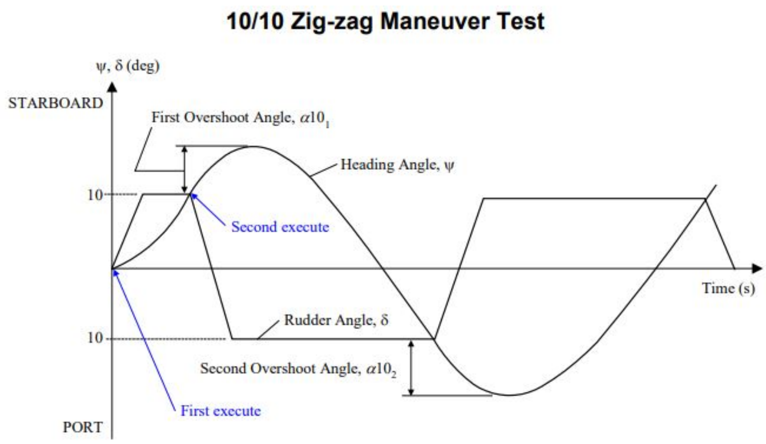

Figure 4.4: Schematic 10°-10°zigzag with first and second overshoot [8]

20°- 20°Zigzag

This scenario consists of a zigzag maneuver again, only this time the rudder angle is set from an initially straight approach to 20 degrees starboard to 20 degrees port or the other way around. According to the IMO standard [19], when performing a zigzag maneuver with a 20 degree turning angle only the first overshoot angle is important to check the initial turning ability of the ASV.

Pull-out test

This test is performed to identify course instability, which is an undesirable factor for an autonomous vessel. The test is performed at the end of the turning circle test. The test is executed by setting the rudder back to the neutral position and kept there until a steady turning rate is obtained. This gives an indication of the vessel's dynamic stability when returning to a straight course. The pull-out test is displayed in figure 4.5, here it is shown that an ASV is table when the turning rate decays to zero for turns to both starboard and port. If the turning rate for one of the turns to a side does not decay to zero the vessel is considered unstable. The residual turning rate of the turns to starboard and port indicates the magnitude of instability at the neutral rudder angle.

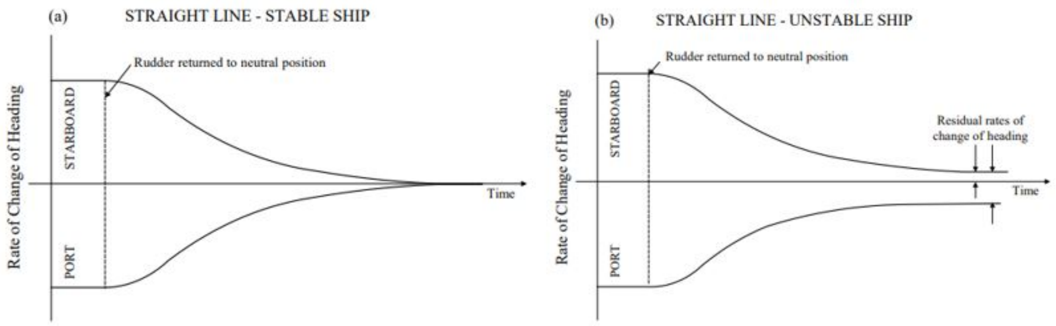

Figure 4.5: Schematic pull-out test where (a) shows a stable vessel and (b) shows an unstable vessel with a residual rate of change of heading [8]

4.3. Path following KPIs

The first objective of this test is to check the ability of the ASV to follow a path existing from waypoints. The performance of this ability can be expressed by setting a radius of acceptance to the waypoints. This radius should depend on the vessel size, for example in the experiments of [9] this radius was set two ship lengths. As mentioned in the last chapter the tests should consists of multiple paths with consecutive waypoints under different angles to validate the path following ability. The second objective of this scenario is to match the optimal path. So besides that the waypoints should be passed as close by as possible, it is also the goal to minimize the overshoot when changing the vessels heading. The two KPIs for this scenario are the following:

- The cumulative absolute deviation from the waypoints
- The deviation from the optimal path length

4.4. Collision avoidance

In the category of collision avoidance most KPI are related to safety and based on the COLREGs [11]. To objectify safety with a KPI it is not sufficient to check whether a collision occurred or not. The KPIs should include factors such as the reaction time and safe distance between vessels. All scenarios in this category start by observing the obstacle or other vessel and determining if there is a risk for a possible future collision.

Avoid stationary obstacle

The objective of this scenario is to check the ability of the ASV to register an obstacle and to take subsequent action. The ASV has a straight course when it is approaching the obstacle and after the evasive maneuver it should return to this course. So this test scenario has two KPIs, with the first being the range from which the ASV is able to register the obstacle. The second KPI is the extra distance covered to return to the original course.

Overtaking

The objective of this scenario is to safely overtake a slower moving vessel on the same course. During this scenario a series of actions is required. First the situation should be registered, secondly the decision should be made whether the space required to make the overtaking maneuver is available. Then the maneuver is performed, while maintaining a safe distance to the other vessel and at last the

ASV should return to its original course of the moment it approached the situation. The relevant KPIs for this scenario are as follows:

- The registration range
- The minimum distance between the vessels
- The extra distance covered by the overtaking maneuver

Avoid crossing obstacle

The objective of this scenario is applying COLREG correctly, depending on the situation. There are two possibilities in this scenario, namely the crossing vessel is passing from the starboard direction or from the port direction. The vessel coming from the port direction has to give way to the vessel from the starboard direction according to COLREG [11]. Both situations should be considered during the tests. This scenario requires multiple actions by the ASV. First the ASV has to register the crossing vessel, then it has to apply the regulations to the situation by giving way to the crossing vessel or by taking priority. Depending on the situation it has to make a maneuver. When the crossing vessel is approaching from starboard the ASV has to make an evasive maneuver, this maneuver exits of turning to starboard to pass on a safe distance behind the crossing vessel and then return to the original course. If the crossing vessel is approaching from port no evasive maneuver is required and the ASV can continue its course. The KPIs for this scenario are again the registration range, the minimum distance between the vessels and the extra distance covered by the overtaking maneuver. The extra KPI for this scenario is the correct implementation of COLREG.

Avoid head-to-head collision

The objective of this scenario is to register a possible collision and take action to avoid this. The scenario consists of two vessels approaching each other on a opposite course. Whenever another vessels approaches the ASV from an opposite direction, the ASV should predict the other vessels route and determine whether it is a collision course. If a collision course is the case, then both vessels should make an evasive maneuver to starboard according to COLREG. Since the ASV can only control itself and it can not be expected that the other vessel will always make the maneuver, the ASV has to make the evasive maneuver large enough to avoid the other vessel by a safe distance. The evasive maneuver ends when the ASV returns to it original course. The KPIs are as follows:

- The registration range
- The minimum distance between the vessels
- The extra distance covered by the evasive maneuver

Avoid shallows

The objective of this scenario is to avoid getting stuck in shallow waters. This can be tested by setting two waypoints with in between these points a shallow part, so the ASV has take another not direct course when passing these waypoints. The objective for the ASV is to detect the shallow part by depth measurement or using historical data of the waterway. After detection the ASV should avoid the shallow part and return to the original optimal course. The KPIs in this scenario are the shallow registration range and the extra distance covered by the ASV.

4.5. Vessel collaboration KPIs

This category consists of scenarios with collaborating ASVs. The objectives are related to fleet operations and the KPIs include parameters such as the relative position between vessels.

Keep constant distance

The objective of this scenario is to follow another vessel while maintaining a constant distance. The functioning of a system capable of doing this is similar to an adaptive cruise control; the vessel behind has to adjust its speed to maintain a certain set distance. It also has to follow the same route as the leading vessel. The KPIs for this test scenario are the minimum, maximum and average relative distance between the leading vessel and the follower ASV.

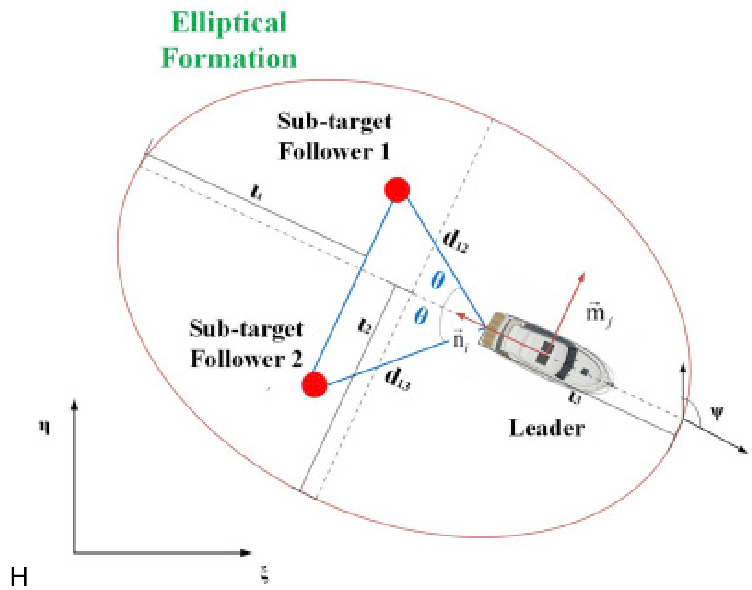

Figure 4.6: Scheme of ASV formation [16]

Form a fleet and keep formation

The objective of this scenario is to form a fleet consisting of ASVs in a certain formation with a leading vessel and keep this formation while travelling the designated route. In the simplest case three ASVs form a fleet in a triangle with the leading vessel on top as shown in figure 4.6. To keep the formation the relative distances between the vessels should be maintained at a set distance, while also maintaining a constant angle between the leading vessel main axis and the shortest distance to the corresponding following vessel. If these two factors are maintained between a predetermined maximum range, the formation is kept and the following vessels will automatically follow the course of the leading ASV. The KPIs in this test scenario are as follows:

- The forming time of the fleet formation
- The minimum, maximum and average distance between following ASV 1 and the leading ASV
- The minimum, maximum and average distance between following ASV 2 and the leading ASV
- The minimum, maximum and average angle between the leading ASV longitudinal axis and following ASV 1
- The minimum, maximum and average angle between the leading ASV longitudinal axis and following ASV 2

When using a fleet of more ASVs, a different formation should be constructed, but the essence of keeping the same relative distance and angle with respect to the leading ASV remains.

Change position in formation

The objective of this scenario is to have ASVs switch position in the fleet formation. For this scenario again a fleet consisting of three ASVs is considered. To execute this scenario two vessels should switch places in the formation. During this switch a safe distance between vessels should be maintained, while also maintaining the course of the fleet. If the two following ASVs change position, the leading vessel stays in place and the chain command stays clear. In the case that the leading ASV changes position with a following ASV the command of the fleet should be shifted. The KPIs for this scenario are the minimum distances between the ASVs, the time needed to change formation and the deviation of the optimal route.

4.6. KPIs summarized

In this section an overview of all scenarios with corresponding KPIs is provided. This overview is shown in table 4.1.

Table 4.1: All testing scenarios with corresponding KPIs and units

Category	Scenario	KPIs	Unit
Manoeuvring	Navigate in straigth line	Average and maximum deviation from straight line	*[m]*
	Mooring test	Deviation of stopping location to set location	*[m]*
	Reach maximum speed	Maximum speed	*[m/s]*
	Stopping test	The track reach	*[m]*
		The head reach	*[m]*
	Turning test	The tactical diameter	*[m]*
		The advance	*[m]*
	10-10 zigzag	First overshoot angle	*[deg]*
		Second overshoot angle	*[deg]*
		Travelled distance during first overshoot	*[m]*
	20-20 zigzag	First overshoot angle	*[deg]*
	pull-out test	Residual turning rate	*[deg/s]*
Path following	Path following	The cumulative absolute deviation from the waypoints	*[m]*
		The deviation from the optimal path length	*[m]*
Collision avoidance	Avoid stationary obstacle	Registration range	*[m]*
		Extra distance covered by performing maneuver	*[m]*
	Overtaking	Registration range	*[m]*
		Minimum distance between the vessels	*[m]*
		Extra distance covered by performing maneuver	*[m]*
	Avoid crossing obstacle	Registration range	*[m]*
		Minimum distance between the vessels	*[m]*
		Extra distance covered by performing maneuver	*[m]*
		Correct implementation of COLREG	*yes/no*
	Avoid head-to-head collision	Registration range	*[m]*
		Minimum distance between the vessels	*[m]*
		Extra distance covered by performing maneuver	*[m]*
	Avoid shallow	Registration range	*[m]*
		Extra distance covered by performing maneuver	*[m]*
Vessel collaboration	Keep constant distance	Minimum, maximum and average distance to leading ASV	*[m]*
	Form a fleet and keep formation	Minimum, maximum and average distance between following ASV to leading ASV	*[m]*
		Minimum, maximum and average angle between longitudinal axis of leading ASV and following ASV	*[deg]*
	Change position in formation	Minimum distance between the ASVs	*[m]*
		Time to execute the change in formation	*[s]*
		Deviation from the optimal route	*[m]*

5 Testing Method

With the set KPIs, the described environment and the possible testing scenarios the method can be designed. In this chapter the guidelines for performing the tests will be described for all scenarios per category. First all scenarios will be treated for a general testing method, then the testing method per scale will be given with the applicable scenarios and measurement methods. The goal of the method is to validate the functioning of the ASVs. For validation certain thresholds need to be adapted, so the testing can be objectified. In this section the testing steps will be described per scenario with the according KPIs, then the framework of how the test should be performed, what parameters should be measured and how this measurements can be done are described. After that the formulas are that should be used to validate the assessment aspect are given. All scenarios are executed with a certain speed, which should be mentioned in the subsection of the scenario. In the cases where no speed is mentioned it can be assumed that the test speed should be used. The test speed is equal to the optimal speed of the respective ASV.

5.1. Manoeuvring test

The first category of scenarios for ASVs that should be tested is the manoeuvring ability. The manoeuvring abilities of the ASV need to be sufficient before performing scenarios in the other categories. In the previous two chapters the scenarios, the objective of the scenarios and the matching KPIs are described. The first scenario that should be performed is the navigation in straight line.

Navigate in a straight line

The setup for this scenario requires a straight body of water long enough to asses the performance of the ASV. In this body of water a starting point and end point should be set on a straight line with a distance that covers the minimum distance to validate the ability. The KPI is the average and maximum deviation from the straight line, this deviation should be tracked. The parameters that should be measured are the x-y coordinates of the vessel at a given time rate Δt. The measurements can be done using GPS location or for the model scale with cameras. The result of the measurement should be a set of time points with corresponding measured x-y coordinates. The deviation of the course is equal to the minimum distance between the measured coordinates and the straight line course, which can calculated with the formula below. In this formula start and end start correspond to the start and end coordinates of the predetermined course.

$$d(t) = \frac{|(x_{end} - x_{start})(y_{start} - y_{meas}(t)) - (x_{start} - x_{meas}(t))(y_{end} - y_{start})|}{\sqrt{(x_{end} - x_{start})^2 + (y_{end} - y_{start})^2}}$$

The KPIs are the extreme deviation and the average deviation which should be below an acceptable value to consider the validation of this aspect good. The acceptance value should be based on the expectations of the ASV. The formulation is given below, where n is the the amount of time steps and a_1 and a_2 are the respective acceptance values.

If $max\Big\{d(t)\Big\} < a_1$ and $\frac{\sum_{t=0}^{n}(d(t)}{n} < a_2$ than the navigation in straight line is successful.

Mooring test

The setup for the mooring test requires a body of water where it is possible to berth. An end point should be set somewhere along the berthing location. The objective of this scenario is to have the ASV stopped at the set end location. The distance between the true stopping location $M_m(x_m, y_m)$ and the set location $M_s(x_s, y_s)$ is the KPI and can be obtained using a distance measuring instrument, with the help of GPS or camera. If the coordinates of the true stopping location are measured the first formula below should be used to determine the distance. To validate the KPI an acceptance value a should be set according to the expectations.

Distance between M_m and M_s: $d = \sqrt{(x_m - x_s)^2 + (y_m - y_s)^2}$
The mooring test is successful if: $d < a$

Reach maximum speed

To perform this scenario it is required to have a waterway available that is long enough to reach the maximum speed of the ASV. The scenario is executed by letting the ASV give full throttle till no further acceleration in measured and the ASV has reached a constant maximum speed. The measurement are executed with accelerometers. The KPI of this scenario is the maximum speed, the performance of this test is sufficient when the difference between the measured maximum speed V_m and the design maximum speed V_d is smaller than a set acceptance value a. The speed can be calculated from the coordinates of the vessel at different time points. The coordinates should be determined with GPS or camera. The data set should have the form of table 5.1.

Table 5.1: Resulting data set of speed measurements

time point	x-coordinate	y-coordinate	speed at time point
0	x_1	y_1	V_0
t_1	x_2	y_2	$V(t_1) = \frac{\sqrt{(x_1-x_0)^2+(y_1-y_0)^2}}{t_1-t_0}$
t_2	x_3	y_3	$V(t_2) = \frac{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2}}{t_2-t_1}$

If $V_d - max\Big\{V(t)\Big\} < a$ the maximum speed is in range of the design speed.

Stopping test

This test requires the same setup as the maximum speed test and could be performed directly after. The procedure of the test starts with the ASV having a certain forward speed and the direction of the propulsion is changed to full astern. This causes that the ASV is going to decelerate and also deflects from the straight line course, since changing the propulsion direction is not an instantaneous action. The KPIs during this test are the head reach HR and the track reach TR. These can be measured using GPS, cameras and distance meters. The measurement take places from the moment the full astern order is given to the ASV t_0, until the moment the speed of the ASV reaches zero and it starts accelerating backwards t_s. The performance of the ASV during this test is sufficient if the track reach is smaller than 10 ship lengths . The grade of performance is further determined by the head reach, they are inversely related. When the value of the head reach is decreasing, the performance is increasing. The test should be repeated with a different speeds, so the stopping ability through the entire speed range is known. The head reach is the distance the vessel travels in the course direction and track reach is the travelled distance till standstill:
$HR = |x(t_1) - x(t_0)|$, using a local coordinates system where the x-axis is equal to the course direction.
$TR = \sum_{i=1}^{t_s}(\sqrt{(x(t_i) - x(t_{i-1}))^2 + (y(t_i) - y(t_{i-1}))^2}) < 10L$, where L is the vessel length.

Turning test

The setup for the turning test requires a waterway that is width enough to perform the maneuver. The procedure starts with the ASV approaching on a straight course. Then the command is given to the ASV to set the rudder to the maximal design angle, this must not exceed 35 degrees. At the moment the command is given the measurements should start t_0. The KPIs of this test are the advance Ad and the tactical diameter TD. The best way to measure both is to use GPS and determine the x-y coordinates of the ASV. A local coordinate system should be used where the x-axis is equal to the initial course direction. The advance is measured along the approach course and stops when a 90 degrees change of heading is reached t_q. The tactical diameter is measured perpendicular to the approach course and stops when 180 degrees change of heading is reached t_h. For the case where the test speed is used the tactical diameter should be less than five times the ship length and the advance should be less than four and a half ship lengths. It is also useful to know the advance and tactical diameter for a range of speeds, so repetition of the test with different speeds is recommended.

If $Ad = |x(t_q) - x(t_0)| < 4.5L$ and $TD = |y(t_h) - y(t_0)| < 5L$ the requirements for the turning ability are satisfied according to the IMO standard [7], however depending on the purpose of the ASV the requirement can be set stricter.

10°- 10°Zigzag

The setup for the zigzag test requires a waterway width enough to perform the maneuver. The test starts with the ASV maintaining the test speed and the rudder in the neutral position. Then the command is given to perform the zigzag maneuver by changing the rudder to 10 degrees starboard t_0. The test should be repeated and during this repetition the initial turn should be to port. At the moment the command is given the measurements of the heading angle $\Psi(t)$ starts. When the heading angle of the ASV has reached the 10 degrees change, the second rudder change should be executed, the rudder is now set to 10 degrees port. The heading angle was still increasing to starboard, so an overshoot will occur before the heading angle will change to 10 degrees port. This overshoot is determined by measuring the maximum heading angle to starboard that is reached subtracting the objective of 10 degrees. When the Heading angle has reached 10 degrees port, the rudder will again be set to 10 degrees starboard to create the zigzag movement. Again the overshoot angle should be measured here, now with the maximum heading angle to port that is reached. The KPIs for this test are the first, second overshoot angle and the time to reach an initial 10 degrees heading angle change to both sides t_1. The heading angle can be measured using GPS or with a gyro compass. The performance of the ASV its initial turning ability increases when the overshoot angles decreases. The first and second overshoot angles are calculated using the formulas below, the direction of the first turn is set as the positive angle.

The first overshoot angle: $\alpha_1 = max\Big\{\Psi(t)\Big\} - 10°$

The second overshoot angle: $\alpha_2 = min\Big\{\Psi(t)\Big\} + 10°$

Also for the initial turning ability to be sufficient according to IMO standard it requires that the distance travelled during the first overshoot is not more 2.5 ship lengths. The distance travelled l_{10} should be calculated with GPS coordinates measured at time interval Δt.

$l_{10} = \sum_{i=t_1+\Delta t}^{t_{max}} (\sqrt{(x(i) - x(i-1))^2 + (y(i) - y(i-1)^2)}) \leq 2.5L$, where t_{max} is the time point where the first overshoot angle reaches its maximum.

20°- 20°Zigzag

The setup and execution of the 20°- 20°Zigzag is exactly the same as the that of the 10°- 10°Zigzag. The only difference are the KPIs, with this larger turning degrees only the first overshoot angle is relevant to check the initial turning ability.

Pull-out test

The Pull-out test should be performed directly after the turning test. At the end of the turning test the rudder is located at maximum allowable angle, this is the initial position for the pull-out test. Here the rudder is returned to neutral position and kept there until a steady turning rate is obtained. In the ideal

case with perfect performance the steady turning rate should be at zero. If the vessel is dynamically unstable, then the steady turning rate will not be at zero but at some residual value. The magnitude of this residual value determines the performance of the ASV during this test. If the magnitude increases the performance decreases. This test should be performed from both starboard and port. The rate of change of heading $\dot{\Psi}(t)$ can be measured with gyro compass or using GPS and should be measured from the start of the test t_0 until the moment the steady turning rate t_s is obtained.
If $\dot{\Psi}(t_s) = 0$ than the vessel is dynamically stable, when a residual is left: $\dot{\Psi}(t_s) \neq 0$ the vessel is dynamically unstable. In this case the magnitude of the residual determines the performance, whereas $|\dot{\Psi}(t_s)|$ increases the performance decreases.

5.2. Path following test

The preparation for the path following test includes the design of multiple trajectories the ASV has to follow. A trajectory consists of a set of waypoints with x and y coordinates. These coordinates could be referring to GPS coordinates, the global coordinate system. However it is also possible to utilize coordinates of a local coordinate system of a waterway. In table 5.2 an example is given what the a set of waypoint would look like. The first KPI for this test the accuracy at which the ASV passes the waypoints. This can be measured with GPS or with a camera by visualizing the waypoints and path, it is also an option to put tagged buoys at the waypoints and use the distance sensor or LiDAR. The second KPI is the deviation from the optimal path length.

Table 5.2: Example of trajectories in local coordinate system [17]

1st and 2nd trajectories:	3rd trajectory:	4th trajectory:	5th trajectory:
$Wpt_1 = (0, 0)$ m	$Wpt_1 = (0, 0)$ m	$Wpt_1 = (0, 0)$ m	$Wpt_1 = (0, 0)$ m
$Wpt_2 = (0, 5)$ m	$Wpt_2 = (5, 0)$ m	$Wpt_2 = (-1.5, 1.5)$ m	$Wpt_2 = (-1.5, 0)$ m
$Wpt_3 = (-2.5, 12.5)$ m	$Wpt_3 = (6, 2.5)$ m	$Wpt_3 = (-3, 3)$ m	$Wpt_3 = (-3, 0)$ m
$Wpt_4 = (-5, 17.5)$ m	$Wpt_4 = (7.5, 5)$ m	$Wpt_4 = (-4, 4)$ m	$Wpt_4 = (-4, 0)$ m
$Wpt_5 = (-10, 20)$ m	$Wpt_5 = (12.5, 10)$ m	$Wpt_5 = (-5, 5)$ m	$Wpt_5 = (-5, 0)$ m
$Wpt_6 = (-20, 17.5)$ m		$Wpt_6 = (-6, 6)$ m	$Wpt_6 = (-6, 0)$ m
$Wpt_7 = (-20, 5)$ m		$Wpt_7 = (-8, 8)$ m	$Wpt_7 = (-8, 0)$ m
		$Wpt_8 = (-10, 10)$ m	

To rate the performance of the ASV the accuracy of the ASV reaching the waypoint Wp_i should be calculated. Therefore the path travelled by the ASV should be tracked by using the GPS coordinates sampled at time interval δt. The sampled points will be referred to as $P(t)$ and have a corresponding x coordinate $x(t)$ and y coordinate $y(t)$. The accuracy per waypoint can be defined as the minimum distance between $P(t)$ and Wp_i, the measurements become more realistic with a decrease of δt. The total accuracy of the path following abilities is defined as the average deviation from the waypoints and should be smaller than a predetermined acceptance value a.

Accuracy per waypoint i: $Ac_i = min\Big\{\sqrt{(x(t) - x_{Wp_i})^2 + (y(t) - y_{Wp_i}^2}\Big\} \quad \forall t$

KPI 1: $\dfrac{\sum_{i=1}^{n} Ac_i}{n} < a_1$ for n waypoints.

To fulfill the requirements for the second KPI the difference between the total travelled length d_t and the optimal route OR should be lower than the set acceptance value a.

The total travelled route: $d_t = \sum_{j=t_0+\Delta t}^{t_{end}} \sqrt{(x(j) - x(j-1))^2 + (y(j) - y(j-1)^2}$

KPI 2: $d_t - OR < a_2$

5.3. Collision avoidance test

The test in the category collision avoidance test requires more preparation and also timing. The obstacle that can be used are other ASVs or conventional vessels.

Avoid stationary obstacle

As the title implies the setup for this test scenario requires an obstacle on the water surface, that is on the course of the ASV. Procedure starts with the ASV sailing with a straight approach towards the obstacle. The first point of attention is when the ASV registers the obstacle, the distance left before reaching the obstacle is the first KPI in this scenario. After the registration the ASV should make an evasive maneuver by altering its course around the obstacle. When the ASV has passed the obstacle it should return to its original course. The second KPI of this test is the extra distance covered by making the evasive maneuver with respect to the original straight course. The measurement can be made with a distance sensor, LiDAR, GPS or a camera. For the first KPI the registration distance RD should be large enough to perform the evasive maneuver, this minimum distance is referred to as minimum maneuver distance MD. The second KPI is calculated by taking the difference between the travelled route and the initial optimal route IR. The travelled route can be calculated using the sampled GPS coordinates at time interval Δt. An acceptance value a should be determined to objectify this KPI. If the requirements of both KPIs are met the test is sufficient

KPI 1: $RD > MD$

KPI 2: $\sum_{i=t_1+\Delta t}^{t_{end}} \sqrt{(x(i)-x(i-1))^2+(y(i)-y(i-1)^2} - IR < a$, where t_{end} is the last time point of the route.

Overtaking

The setup for this scenario requires a body of water that is long enough for the maneuver made in the test, it does not necessarily has to be straight. It also requires an extra vessel, that has locally the same course as the ASV, but a lower velocity. The extra vessel should be initially placed before the ASV, to make the scenario possible. The procedure starts with both vessels moving at certain speeds, with the ASV being faster. The first point of notice is when the ASV registers the other vessel on its path, the overlap of their courses and the decreasing distance between them. The distance between them at the moment the ASV decides to overtake the other vessel is the first KPI. This KPI referred to as registration range is handled the same way as in the avoid stationary obstacle scenario. Also at this moment the ASV changes its course to overtake. During the overtake maneuver the distance between both vessels $d(t)$ should be measured, since a safe distance should be kept during the maneuver. The second KPI is this minimum distance between the vessels and can be measured with a distance sensor or by calculating the distance between the GPS coordinates from both vessel taken at the same time. For both ways the sample time Δt determines the accuracy of the KPI. The safe distance between the vessels is referred to as SD. The last step of the test is for the ASV to return to its original course after overtaking the other vessel. The extra distance covered by the altered course with respect to the original course is the last KPI of this scenario. The measurements can be done with a distance sensor, LiDAR, GPS or a camera. If all three KPIs their requirements are met the overtaking ability is sufficient.

KPI 1: $RD > MD$

KPI 2: $min\Big\{d(t)\Big\} > SD$

KPI 3: $\sum_{i=t_1+\Delta t}^{t_{end}} \sqrt{(x(i)-x(i-1))^2+(y(i)-y(i-1)^2} - IR < a$, where t_{end} is the last time point of the route.

Avoid crossing obstacle

The setup requires a body of water where it is possible for an other vessel to cross the course of the ASV. The initial state of the scenario is with ASV having a straight course and the other vessel approaching this course perpendicular, in such a way that if no action is taken a collision would occur. The task for the ASV is to register the other vessel and its collision course, than to apply COLREG by determining from which side the vessels crosses its path. If the ASV has to make the evasive maneuver according to the regulations than the extra distance travelled should be measured. During the crossing event the distance between both vessels should be measured, this can be done with distance sensor or LiDAR. The registration range should also be measured this can be done with distance sensor, LiDAR, GPS or a camera. The correct implementation of COLREG to situation by the ASV should also be checked this can be done using the camera or checking the GPS data. The first three KPIs should be measured and calculated the same way as in the overtaking scenario. The fourth KPI is determined by following the regulations in right manner. If all four KPIs are satisfied than the scenario is sufficient.

KPI 1: $RD > MD$
KPI 2: $min\left\{d(t)\right\} > SD$
KPI 3: $\sum_{i=t_1+\Delta t}^{t_{end}} \sqrt{(x(i)-x(i-1))^2+(y(i)-y(i-1)^2} - IR < a$, where t_{end} is the last time point of the route.
KPI 4: if crossing vessel comes from starboard side give way, otherwise go first

Avoid head-to-head collision

This scenario requires a second vessel and a body of water width enough to make an evasive maneuver. The initial setup has the ASV and the second vessel sailing in opposite directions on the same waterway. The course of both vessels should be towards the other vessel, so they will meet head on and actions need to be made to prevent collision. The goal for the ASV in this case is register the other vessel and predict the possible collision. Then the ASV has to make an evasive maneuver to pass the other vessel on starboard following COLREG. At the end of the procedure the ASV should return to its original course. The KPIs are the registration range, minimum distance between the vessels and the extra distance covered by performing the evasive maneuver. The required parameters can be measured with LiDAR, GPS location, camera and distance sensor and the KPIs can be determined in the same way the KPIs in the overtaking scenario are determined. The performance of the vessel in this test scenario is sufficient if the requirements of all KPIs are satisfied.

KPI 1: $RD > MD$
KPI 2: $min\left\{d(t)\right\} > SD$
KPI 3: $\sum_{i=t_1+\Delta t}^{t_{end}} \sqrt{(x(i)-x(i-1))^2+(y(i)-y(i-1)^2} - IR < a$, where t_{end} is the last time point of the route.

Avoid shallows

This scenario can be created in two possible ways, namely by using a body of water with a fairway and on the sides of this fairway shallow parts, where the ASV would get stuck if it passes there. The second possibility is by creating an obstacle underneath the water surface which the ASV has to detect and evade. In both situations the initial course of the ASV should be set trough the shallow part, so it is forced to take action. For the first situation the ASV has to use a combination of historical data of the waterways, GPS and a depth measurement tool to detect and evade the shallow parts. In the second situation LiDAR or sonar should be used to detect the obstacle. The first KPI to be tracked is the registration range RD, which should be larger than the distance required to perform an evasive maneuver MD.

KPI 1: $RD > MD$
KPI 2: $\sum_{i=t_1+\Delta t}^{t_{end}} \sqrt{(x(i)-x(i-1))^2+(y(i)-y(i-1)^2} - IR < a$, where t_{end} is the last time point of the route.

5.4. Vessel collaboration test

The tests in this category require multiple ASVs in the setup. Before testing the features here the performance of the control of the single ASVs should be sufficient, otherwise the tests are a waste.

Keep constant distance

The setup for this scenario requires two ASVs, where one is designated as the leading ASV. Both ASVs should be in the same body of water with the leader ASV in front of the other. The leader ASV should be given a course, the other ASV has to follow at a set distance. The goal is to keep this distance constant when following the course. The distance between the two ASVs should be registered during the whole test, so the minimum, maximum and average distance between them can be determined. The measurements can be done with a distance measuring sensor, GPS location or with a camera. The parameters to be measured are the GPS coordinates of both ASVs at the same time moments, so the relative distance can be calculated. The intervals between these time moments is referred to as Δt, an decrease in Δt means that the KPIs are more accurate. The distance $d(t)$ between ASV 1 and ASV2 is calculated with Euclidean distance:

$$d(t) = \sqrt{(x_1(t) - x_2(t))^2 + (y_1(t) - y_2(t)^2}$$

The KPIs are the minimum, maximum and average distance between the two vessels, these KPIs should be limited by acceptance values to validate the performance on this aspect. The acceptance values are determined by the maximum allowed deviation from the set ideal distance D between the ASVs. If the requirements of all KPIs are met, than the performance is sufficient.

KPI 1: $min\{d(t)\} > D - a_1$
KPI 2: $max\{d(t)\} < D + a_2$
KPI 3: $D - a_3 < \frac{\sum_{t=1}^{n} d(t)}{n} < D + a_3$, with n being the amount of measurement points.

Form a fleet and keep formation

This setup requires a minimum of three ASVs to be able to form a fleet. The ASVs should be randomly put in different places within limited reach of one another. The procedure starts with giving the command to form a fleet and appointing one of the ASVs as leader of the fleet. The leader should be given a course it has to follow, while travelling this course the following ASVs have to stay in the boundaries of the fleet. The heading and position of all ASVs should be tracked during the test, so the relative positions and angle between them is measured. The position related KPIs for this scenario are the average and extreme values of the distance and angle between the following ASVs and the leader. The time related KPI is the forming time of the formation, assuming the ASVs are in range of each other when the forming command is given. The time is measured and from the moment the command is given t_0 till the moment the formation is formed t_f. The measurement of the parameters necessary to calculate the KPIs, can be carry out with the camera, distance sensors and GPS. In figure 5.1 the formation with relative distances and angles are shown. The KPIs requirements should be set in the form of acceptance values, so the test scenario can be validated. For the position KPIs the acceptance value is the maximal deviation from the desired parameter D_{ij} and Θ_i The formulas to calculate the parameters and the requirements to grade the performance are given below.

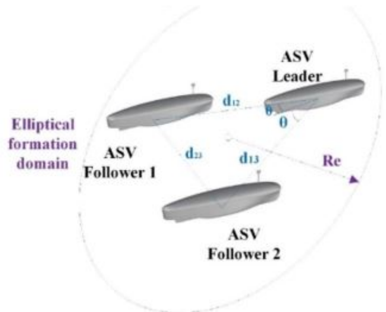

Figure 5.1: Scheme of ASV formation including relative distances [16]

$$d_{ij}(t) = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t)^2}$$

$\theta_i = \arcsin \frac{\eta_i}{d_{1i}}$, with η being the perpendicular distance between the main axis of the leading ASV to the following ASV.

KPI 1: $t_f - t_0 < a_1$
KPI 2: $min\{d_{ij}(t)\} > D_{ij} - a_2$
KPI 3: $max\{d_{ij}(t)\} < D_{ij} + a_3$
KPI 4: $D_{ij} - a_4 < \frac{\sum_{t=1}^{n} d_{ij}(t)}{n} < D_{ij} + a_5$, with n being the amount of measurement points.

KPI 5: $min\{\theta_i(t)\} > \Theta_i - a_6$
KPI 6: $max\{\theta_i(t)\} < \Theta_i + a_7$
KPI 7: $\Theta_i - a_8 < \frac{\sum_{t=1}^{n} \theta_i(t)}{n} < \Theta_i + a_9$, with n being the amount of measurement points.

Change position in formation

This scenario is a follow-up to the previous one. Namely, when the fleet is formed and the fleet is sailing its course, it can be advantageous to let the ASVs switch positions. The main concerns during this maneuver is the safety of the ASVs and the costs of the maneuver. These costs are expressed in the time to perform the change of position and the deviation from the course during the maneuver. The time is measured from the moment the command is given to change positions t_0 until the moment the new fleet formation is adopted t_f. To rate the time KPI a desired time t_D should be set, wherein the formation should change. The KPIs based on the relative distance and the course can be tracked with the camera, GPS and distance sensor. The second KPI is the minimum distance between the vessels d_{ij} and should have an acceptance value that provides a safe distance. The last KPI compares the travelled route with the optimal initial route IR, it may be assumed that the travelled route of the fleet is equal to the travelled route of the leading ASV. The deviation of this optimal route should smaller than the set acceptance value.

KPI 1: $t_f - t_0 \leq t_D$
KPI 2: $min\{d_{ij}(t)\} > a_1 \qquad \forall i, j$ and $i \neq j$
KPI 3: $\sum_{i=t_0+\Delta t}^{t_f} \sqrt{(x_1(i) - x_1(i-1))^2 + (y-1(i) - y_1(i-1)^2} - IR < a_2$

5.5. Overview KPI assessment

In table 5.3 the KPIs, measurement parameters, measurement equipment and the threshold for the KPI are summarised for all scenarios. The measurement equipment and parameters are suggested, however it is possible to use different techniques to determine the KPIs.

Table 5.3: Overview of KPIs including measurement equipment, parameters and KPI assessment

Scenario	KPIs	Measurement Parameters	Measurement equipment	Assessment
Navigate in straight line	Maximum deviation from straight line	x-y coordinates over time	Gps; Camera	$max\left\{d(t)\right\} < a_1$
	Average deviation from straight line	x-y coordinates over time	Gps; Camera	$\frac{\sum_{t=0}^{n}(d(t)}{n} < a_2$
Mooring test	Deviation of stopping location to set location	x-y coordinates when moored	Distance sensor; GPS; Camera	$d < a$
Reach maximum speed	Maximum speed	x-y coordinates over time	Camera; GPS	$V_d - max\left\{V(t)\right\} < a$
Stopping test	The track reach	x-y coordinates over time	Camera; Distance sensor; GPS	$TR < 10L$
	The head reach	x-y coordinates over time	Camera; Distance sensor; GPS	$HR = \lvert x(t_1) - x(t_0)\rvert$
Turning test	The tactical diameter	x-y coordinates over time	Camera; GPS	$TD = \lvert y(t_h) - y(t_0)\rvert < 5L$
	The advance	x-y coordinates over time	Camera; GPS	$Ad = \lvert x(t_q) - x(t_0)\rvert < 4.5L$
10-10 zigzag	First overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_1 = max\left\{\Psi(t)\right\} - 10° < a_1$
	Second overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_2 = min\left\{\Psi(t)\right\} + 10° > a_2$
	Travelled distance during first overshoot	x-y coordinates over time	Camera; GPS;	$l_{10} \leq 2.5L$
20-20 zigzag	First overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_1 = max\left\{\Psi(t)\right\} - 10° < a1$
pull-out test	Residual turning rate	Heading over time	Camera; GPS; Gyro	$\dot{\Psi}(t_s) = 0$
Path following	The cumulative absolute deviation from the waypoints	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$\frac{\sum_{i=1}^{n} Ac_i}{n} < a_1$
	The deviation from the optimal path length	x-y coordinates over time	Camera; GPS	$d_t - OR < a_2$
Avoid stationary obstacle	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Overtaking	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\left\{d(t)\right\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Avoid crossing obstacle	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\left\{d(t)\right\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
	Correct implementation of COLREG	Heading of both vessels	Camera; GPS	$min\left\{d(t)\right\} > SD$
Avoid head-to-head collision	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\left\{d(t)\right\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Avoid shallow	Registration range	x-y coordinates or distance over time	GPS; LiDAR; Sonar	$RD > MD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Keep constant distance	Minimum distance to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$min\{d(t)\} > D - a_1$
	Maximum distance to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$max\{d(t)\} < D + a_2$
	Average distance to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$D - a_3 < \frac{\sum_{t=1}^{n} d(t)}{n} < D + a_3$
Form a fleet and keep formation	Forming time	x-y coordinates over time	Camera; GPS; Timer	$t_f - t_0 < a_1$
	Minimum distance between following to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$min\{d_{ij}(t)\} > D_{ij} - a_2$
	Maximum distance between following to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$max\{d_{ij}(t)\} < D_{ij} + a_3$
	Average distance between following to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$D_{ij} - a_4 < \frac{\sum_{t=1}^{n} d_{ij}(t)}{n} < D_{ij} + a_5$
	Minimum angle between leading and following ASV	x-y coordinates and heading over time	Camera; Distance sensor; GPS; Gyro	$min\{\theta_i(t)\} > \Theta_i - a_6$
	Maximum angle between leading and following ASV	x-y coordinates and heading over time	Camera; Distance sensor; GPS; Gyro	$max\{\theta_i(t)\} < \Theta_i + a_7$
	Average angle between leading and following ASV	x-y coordinates and heading over time	Camera; Distance sensor; GPS; Gyro	$\Theta_i - a_8 < \frac{\sum_{t=1}^{n} \theta_i(t)}{n} < \Theta_i + a_9$
Change position in formation	Time to execute the change in formation	x-y coordinates over time	Camera; GPS; Timer	$t_f - t_0 \leq t_D$
	Minimum distance between the ASVs	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$min\{d_{ij}(t)\} > a_1$
	Deviation from optimal route	x-y coordinates over time	Camera; GPS	$TD - IR < a_2$

5.6. General guideline

In this section the general guideline is provided and discussed. The parts of the general guideline are established in the previous chapters, here the final product is displayed in figure 5.2. The guideline flowchart, shown in Figure 5.2 is inspired by the Testing Guideline Scheme developed by Yusong Pang (TU Delft) during the AVATAR project. To adapt the general guideline to asses a specific case, one should start with determining what the ASV its priorities are, so the important assessment aspect can be determined. This can be done with the use of its operational requirements and environment. With the list of chosen assessment as-pects the testing scenarios can be determined that contribute to rate the aspects. Note that some scenarios are limited by the available environment and equipment. The test procedures of all scenar-ios combined with the required parameters and measurement equipment are described earlier in this chapter. For the measurement equipment it is possible to use alternatives if available. The parameters are used to calculate the KPIs of the testing scenario. Along to the description of the procedures the calculation method and the thresholds for the KPIs are provided. A part of the KPIs have thresholds that are determined by the vessel size, for the other part the thresholds have to be tuned in such a way that they satisfy the operational requirements of the ASV. To asses the performance of the ASV in a testing scenario the following steps are required:

- The measurement data that is gathered during the test has to be stored.
- The KPI values have to be calculated using the stored data.
- For all KPIs in one scenario the KPI values should be checked whether they satisfy the corresponding threshold, so the performance of the test can be rated.
- The performances of the scenarios is used to validate the assessment aspects. When multiple performed scenarios contribute to an assessment aspect, weighing factors should be used to validate the aspect. The weighing factors should be determined depending on the importance and magnitude of the contribution.
- The overall performance depends on the validation of the separate assessment aspects.

The process of assessing the KPIs can be automated by designing a module that gathers the measurement data and automatically processes the measurement data to determine the KPIs and compare them to the thresholds. The accuracy of the measurement equipment and environmental disturbances should not be neglected to optimize the results. The aspects that are not validated after the assessment require improvements and should be reassessed. The output of the assessment of the performance should be a testing report, where the process of each individual testing scenario is reported together with the retrieved measurements and KPIs.

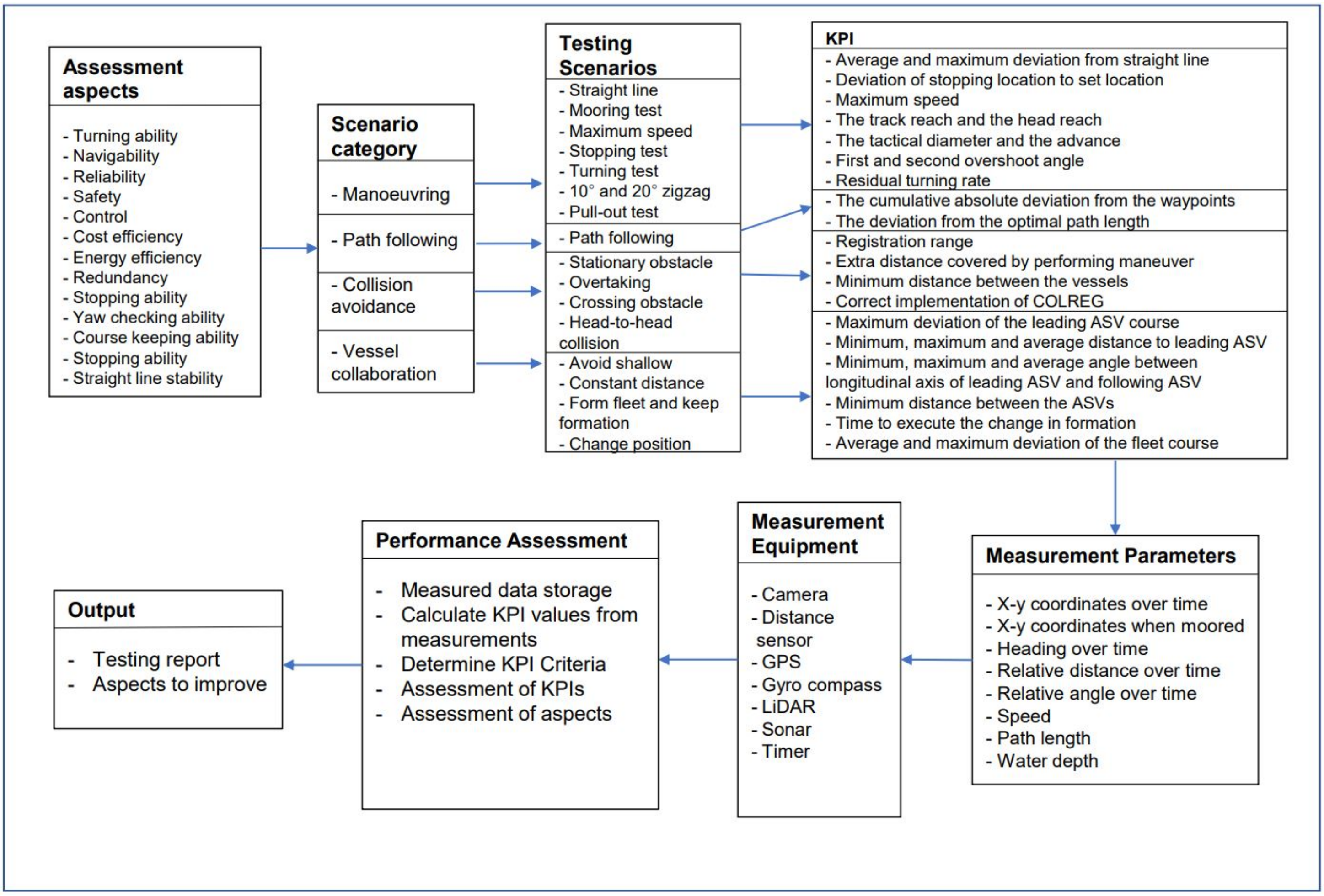

Figure 5.2: Guideline flowchart

6

Applications for AVATAR

In this chapter the finished general guideline is adapted to the ASVs of the AVATAR project. The AVATAR project consists of ASVs in three different scales. Each of these scales requires a different adaption of the general guideline specific for its capabilities, requirements and testing environment.

6.1. The three scales

This research project is done in multiple stages of different scales. The first stage is the model scale. In the RAS lab at the Technical University of Delft small ASVs are available, they can be used in basin to perform the tests. The second stage is the semi-full scale, here a 6 meter long catamaran will be equipped with sensors and a control system to become an ASV. This vessel can be tested in public canals. The last stage is the full scale. A real size autonomous vessel will be built in Germany, this vessel can also be tested in public waters.

6.1.1. Model scale

To the model scale belong the vessels that perform the test scenarios in a lab. In this case two types of models are available. The grey-seabax which is shown in figure 6.1 and the Delfia 1 which can be seen in figure 6.2, both are designed by the TU Delft [20]. The Seabax is build as a conventional vessel and equipped with the systems to make it autonomous, while the Delfia is designed as an ASV without the regular features a manned vessel would need. Multiple models of the Delfia are available so testing scenarios with multiple vessels are possible. The Delfia has a catamaran type of hull, a size of about 45 cm and weighing 5 kg.It is equipped with sensors including LiDar, accelerometers, encoders, distance measurement sensors, gyro, GPS and a camera. The Seabax has a mono hull, a length of 1.75 meters and a weight of 19 kg. This vessel is equipped with the following sensors: accelerometers, encoders, distance measurement sensors, gyro, GPS and also a camera.
The testing environment for the model scale is on the campus of the TU Delft. Here, two towing tanks are available in the RAS lab. In the lab it is possible to fully control the environment during the experiments, for example there is no current and no wind influencing the performance of a vessel during the basic tests. The possibility exists to create waves in these towing tanks with a controllable variable wavelength. Another option is to execute the tests in the bodies of water on the campus, here the environmental disturbances can not be controlled and have to be taken in account. The benefit of using these locations is that the scenarios are not limited by the waterway size, since the relative small ASV sizes in this scale.

Figure 6.1: Grey-seabax

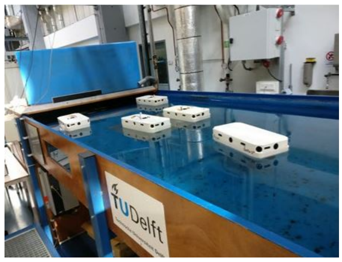

Figure 6.2: Delfia 1

6.1.2. Semi-full scale

For the semi-full scale an existing catamaran is converted to a higher automation level. This catamaran is called the Maverick and the redesign is done by the KU Leuven [21]. The Maverick is 5.8 meters long, has a weight of 620 kg and it has two propellers powered by a motor each with 8 HP. It is equipped with fully electric drive system, on board computer and sensors like LiDAR, stereo cameras, GNSS and IMU.

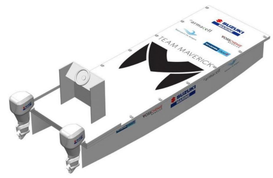

Figure 6.3: Maverick Catamaran new configuration [21]

The Maverick is to large to test in the available lab environment, but it can be tested on public bodies water, for example in canals such as de Schie located in Delft, the Netherlands. The manoeuvring testing scenarios, that are the zigzag test and the turning test succeeded by the pull-out test, require a large body of water to be performed. With the turning test the tactical diameter of the Maverick is determined, the suggested criteria is a tactical diameter lower than 5 times the vessel length. With a length of 5.8 meters this means that the maverick requires an waterway with a width of 29 meters, if it stays within limits on the first try. So practically an even wider body of water is required to perform these tests. So other options should be considered than canals. Also there is only one vessel in this scale available so testing fleet maneuvers is not an option in this scale.

6.1.3. Full scale

For the full scale a new barge-like vessel is being developed with a capacity of approximately 20 tons and a size of approximately 15 m by 4 m. It has a mono hull and will be similar to the Green Wave a vessel from another project of Interreg [22]. The available sensors are unknown at the moment, so it is assumed the equipment will be similar to the equipment of the Maverick of the semi-full scale.

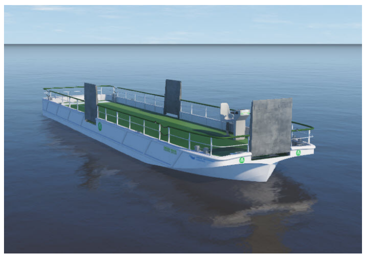

Figure 6.4: The real-size vessel to be built is based on the Green wave

The environment to executes the tests in will also be similar to the semi-full scales, since the full scale is the final product and should operate in urban waterways. Again some test scenarios require more space, for example even if the ASV has an tactical diameter that satisfies the criteria it can be up to 75 meters. Therefore to perform the turning and zigzag test a wide body of water is required. During the first testing phase only one vessel is available so testing fleet operations is not possible.

6.1.4. Feasibility of testing scenarios

The testing environment that is required to perform the test scenarios is discussed for all three scales, along with other limitations. The feasibility for the scenarios per scale is displayed in table 6.1 with the limiting factor. By eliminating the limitation these scenarios become executable.

Table 6.1: Overview scenarios for all categories and feasibility per scale

Category	Scenario	Feasibility per scale			Limitation
		Model	semi-full	full	
Manoeuvring	Navigate in straight line	Yes	Yes	Yes	-
	Mooring test	Yes	Yes	Yes	-
	Reach maximum speed	Yes	Yes	Yes	-
	Stopping test	Yes	Yes	Yes	-
	Turning test	Yes	No	No	Waterway size
	10-10 zigzag	Yes	No	No	-
	20-20 zigzag	Yes	No	No	-
	pull-out test	Yes	No	No	Waterway size
Path following	Path following	Yes	Yes	Yes	-
Collision avoidance	Avoid stationary obstacle	Yes	Yes	Yes	-
	Overtaking	Yes	No	No	Extra vessel
	Avoid crossing obstacle	Yes	No	No	Extra vessel
	Avoid head-to-head collision	Yes	No	No	Extra vessel
	Avoid shallow	Yes	Yes	Yes	-
Vessel collaboration	Keep constant distance	Yes	No	No	Extra ASV
	Form a fleet and keep formation	Yes	No	No	Extra ASVs
	Change position in formation	Yes	No	No	Extra ASVs

6.2. Adaption of testing method

The adaption of the general guideline is created by using the method described in chapter 5.6. Here the scheme of figure 6.5 is followed to construct the methods per scale.

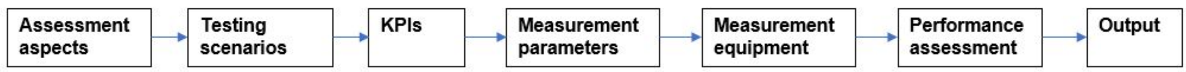

Figure 6.5: Approach for designing the testing guideline

6.2.1. Model scale testing method

First the assessment aspects relevant for the model scale are determined, so the list of scenarios that should be tested can be selected. The important assessment aspect follow from the requirements of the model scale and the available environment and equipment. The requirements of the model scale include the following:

- Functional control of the ASV
- Mapping of the vessel behaviour
- Capability for path following
- The ability to collaborate in a fleet of ASVs
- Detecting and avoiding collision risks

With the list of requirements the set of assessment aspects are determined. In the case of the model scale, where the environment and equipment do not limit the feasibility of any scenario and the requirements cover all aspects, the list of assessment aspects includes all aspects provided in the general guideline. The relevant assessment aspects listed:

Navigability	Turning ability	Straight line ability	Control
Safety	Stopping ability	Course keeping ability	Yaw checking ability
Reliability	Cost-efficiency	Energy-efficiency	Redundancy

Following from the set of assessment aspects the scenarios are determined, these are coupled with the corresponding KPIs. The model scale ASVs feature the suggested measurement equipment, therefore the measurement parameters are equal to the ones described in the general guideline. The criteria for the KPI assessment consist of acceptance values and threshold values depending on the vessel size. The acceptance values make up the thresholds for the KPIs and should be determined by the expectations of the ASV. The ASVs in the model scale are available in two sizes, namely the Delfia with a length of 0.45 m and the Seabax with a length of 1.75 m, the length of the vessel determines some of threshold values. The set of testing scenarios with corresponding KPIs, parameters, sensors and criteria are showcased in table 6.2. A method for data storage should chosen, before executing the test scenarios one by one. After performing a test scenario, the KPI value should be calculated from the measured parameters and be assessed with use of the KPI criteria. After the completion of all testing scenarios the validation of the assessment aspects should occur and all results should recorded in a testing report.

Table 6.2: The testing scenarios that are included to adaption of the model scale guideline

Scenario	KPIs	Measurement Parameters	Measurement equipment	Assessment
Navigate in straight line	Maximum deviation from straight line	x-y coordinates over time	Gps; Camera	$max\left\{d(t)\right\} < a_1$
	Average deviation from straight line	x-y coordinates over time	Gps; Camera	$\frac{\sum_{t=0}^{n}(d(t)}{n} < a_2$
Mooring test	Deviation of stopping location to set location	x-y coordinates when moored	Distance sensor; GPS; Camera	$d < a$
Reach maximum speed	Maximum speed	x-y coordinates over time	Camera; GPS	$V_d - max\left\{V(t)\right\} < a$
Stopping test	The track reach	x-y coordinates over time	Camera; Distance sensor; GPS	$TR < 10L$
	The head reach	x-y coordinates over time	Camera; Distance sensor; GPS	$HR = \|x(t_1) - x(t_0)\|$
Turning test	The tactical diameter	x-y coordinates over time	Camera; GPS	$TD = \|y(t_h) - y(t_0)\| < 5L$
	The advance	x-y coordinates over time	Camera; GPS	$Ad = \|x(t_q) - x(t_0)\| < 4.5L$
10-10 zigzag	First overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_1 = max\left\{\Psi(t)\right\} - 10^\circ < a_1$
	Second overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_2 = min\left\{\Psi(t)\right\} + 10^\circ > a_2$
	Travelled distance during first overshoot	x-y coordinates over time	Camera; GPS;	$l_{10} \leq 2.5L$
20-20 zigzag	First overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_1 = max\left\{\Psi(t)\right\} - 10^\circ < a1$
pull-out test	Residual turning rate	Heading over time	Camera; GPS; Gyro	$\dot{\Psi}(t_s) = 0$
Path following	The cumulative absolute deviation from the waypoints	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$\frac{\sum_{i=1}^{n} Ac_i}{n} < a_1$
	The deviation from the optimal path length	x-y coordinates over time	Camera; GPS	$d_t - OR < a_2$
Avoid stationary obstacle	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Overtaking	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\left\{d(t)\right\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Avoid crossing obstacle	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\left\{d(t)\right\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
	Correct implementation of COLREG	Heading of both vessels	Camera; GPS	$min\left\{d(t)\right\} > SD$
Avoid head-to-head collision	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\left\{d(t)\right\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Avoid shallow	Registration range	x-y coordinates or distance over time	GPS; LiDAR	$RD > MD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Keep constant distance	Minimum distance to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$min\{d(t)\} > D - a_1$
	Maximum distance to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$max\{d(t)\} < D + a_2$
	Average distance to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$D - a_3 < \frac{\sum_{t=1}^{n} d(t)}{n} < D + a_3$
Form a fleet and keep formation	Forming time	x-y coordinates over time	Camera; GPS; Timer	$t_f - t_0 < a_1$
	Minimum distance between following to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$min\{d_{ij}(t)\} > D_{ij} - a_2$
	Maximum distance between following to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$max\{d_{ij}(t)\} < D_{ij} + a_3$
	Average distance between following to leading ASV	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$D_{ij} - a_4 < \frac{\sum_{t=1}^{n} d_{ij}(t)}{n} < D_{ij} + a_5$
	Minimum angle between leading and following ASV	x-y coordinates and heading over time	Camera; Distance sensor; GPS; Gyro	$min\{\theta_i(t)\} > \Theta_i - a_6$
	Maximum angle between leading and following ASV	x-y coordinates and heading over time	Camera; Distance sensor; GPS; Gyro	$max\{\theta_i(t)\} < \Theta_i + a_7$
	Average angle between leading and following ASV	x-y coordinates and heading over time	Camera; Distance sensor; GPS; Gyro	$\Theta_i - a_8 < \frac{\sum_{t=1}^{n} \theta_i(t)}{n} < \Theta_i + a_9$
Change position in formation	Time to execute the change in formation	x-y coordinates over time	Camera; GPS; Timer	$t_f - t_0 \leq t_D$
	Minimum distance between the ASVs	x-y coordinates or distance over time	Camera; Distance sensor; GPS	$min\{d_{ij}(t)\} > a_1$
	Deviation from optimal route	x-y coordinates over time	Camera; GPS	$TD - IR < a_2$

6.2.2. Semi-full and full scale testing method

The semi-full scale and full scale vessels overlap in the requirements and operational environment and therefore it is chosen to design one adaption of the general guideline for both of them. In practical use it is possible to adjust the guideline to the specific case. Following the flowchart first the assessment aspects are determined. The semi-full and full scales prioritise other assessment aspects than the model scale, due to different requirements and purpose. With the larger vessels of these scale the importance lays in the capability to maneuver public waters autonomously in a safely manner. The necessity of fleet operations are not relevant in this stage of the development and should be left out. The important

aspect for these scales are safety, reliability, control, navigability and the vessel behaviour aspects.
The scenarios needed to be performed to asses these aspects include the turning and zigzag tests, which as earlier discussed require relatively a lot space, due to the larger vessels with expected large turning radii. Therefore an environment with a large width should be used to perform these test. Another limitation to executable scenarios depends on the availability of vessels, since for various scenario these are required. For following the collision avoidance scenarios an extra controllable vessel is required: avoid crossing obstacle, avoid head-to-head collision and overtaking. The feasibility of these scenarios depends on an extra controllable vessel, however this does not have to be an ASV and could be a conventional vessel as long it is in the same size range. For now it assumed these limitations can be overcome and therefore these scenarios are included to the adaption of the testing method of the scales.
With the testing scenarios to be performed known, the corresponding KPIs, measurement parameters and measurement methods can be added in. The measurement equipment for the full scale is unknown at this moment and assumed to be similar to the equipment of the Maverick of the semi-full scale. The KPI criteria depend the vessel expected performance and should be determined accordingly. Furthermore to complete the method a data storage method and the option for data processing should determined. At last the results of performing the test and assessing the KPIs and aspects should reported in a test report. The scenarios to be performed with corresponding KPIs, parameters, measurement equipment and criteria are shown in table 6.3

Table 6.3: The testing scenarios that are included to adaption of the model scale guideline

Scenario	KPIs	Measurement Parameters	Measurement equipment	Assessment
Navigate in straight line	Maximum deviation from straight line	x-y coordinates over time	Gps; Camera	$max\Big\{d(t)\Big\} < a_1$
	Average deviation from straight line	x-y coordinates over time	Gps; Camera	$\frac{\sum_{t=0}^{n}(d(t)}{n} < a_2$
Mooring test	Deviation of stopping location to set location	x-y coordinates when moored	Distance sensor; GPS; Camera	$d < a$
Reach maximum speed	Maximum speed	x-y coordinates over time	Camera; GPS	$V_d - max\Big\{V(t)\Big\} < a$
Stopping test	The track reach	x-y coordinates over time	Camera; Distance sensor; GPS	$TR < 10L$
	The head reach	x-y coordinates over time	Camera; Distance sensor; GPS	$HR = \lvert x(t_1) - x(t_0)\rvert$
Turning test	The tactical diameter	x-y coordinates over time	Camera; GPS	$TD = \lvert y(t_h) - y(t_0)\rvert < 5L$
	The advance	x-y coordinates over time	Camera; GPS	$Ad = \lvert x(t_q) - x(t_0)\rvert < 4.5L$
10-10 zigzag	First overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_1 = max\Big\{\Psi(t)\Big\} - 10° < a_1$
	Second overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_2 = min\Big\{\Psi(t)\Big\} + 10° > a_2$
	Travelled distance during first overshoot	x-y coordinates over time	Camera; GPS;	$l_{10} \leq 2.5L$
20-20 zigzag	First overshoot angle	Heading over time	Camera; GPS; Gyro	$\alpha_1 = max\Big\{\Psi(t)\Big\} - 10° < a1$
pull-out test	Residual turning rate	Heading over time	Camera; GPS; Gyro	$\dot{\Psi}(t_s) = 0$
Path following	The cumulative absolute deviation from the waypoints	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$\frac{\sum_{i=1}^{n} Ac_i}{n} < a_1$
	The deviation from the optimal path length	x-y coordinates over time	Camera; GPS	$d_t - OR < a_2$
Avoid stationary obstacle	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Overtaking	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\Big\{d(t)\Big\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Avoid crossing obstacle	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\Big\{d(t)\Big\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
	Correct implementation of COLREG	Heading of both vessels	Camera; GPS	$min\Big\{d(t)\Big\} > SD$
Avoid head-to-head collision	Registration range	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$RD > MD$
	Minimum distance between the vessels	x-y coordinates or distance over time	Camera; Distance sensor; GPS; LiDAR	$min\Big\{d(t)\Big\} > SD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$
Avoid shallow	Registration range	x-y coordinates or distance over time	GPS; LiDAR	$RD > MD$
	Extra distance covered by performing maneuver	x-y coordinates over time	Camera; GPS	$TD - IR < a$

7 Conclusion

This research brought to the surface that an inclusive method for testing and assessing autonomous vessels is not yet provided in literature. This gap is exploited and with the use of available literature a testing method to asses the performance of autonomous vessel is developed. The available consulted literature included valuable information such as: single test scenarios of autonomous vessels, test scenarios for conventional vessel by the International Maritime Organisation, scenarios based on the regulations for collision avoidance and conducted experiments with autonomous vessels. Also assessment aspects are determined that cover the needs for good performances. With this information the designed testing scenarios are motivated and based on the objectives of the scenarios the KPIs are determined. The method to retrieve the KPIs during the tests and how to asses them is what finalises the formation of the testing method. This approach shows that the final product is based on literature, therefore it can be concluded that the testing method provided in this research is supported by literature.

The research is done for the AVATAR project, which has the goal to design and develop an autonomous surface vessel for urban areas, that is capable of transporting both passengers and freight. The AVATAR project is done in three stages simultaneously with three scales of autonomous vessels, namely the model scale, the semi-full scale and the full scale. The model scale has multiple autonomous vessels already available and also an environment to execute all the scenarios in the testing method. The semi-full scale and full scale autonomous vessels are one of a kind in their respective scale, therefore it is not possible to conduct testing scenarios that require multiple autonomous vessels. Also the size of the vessel of these scales is that large, that performing a maneuver that includes a full turning circle requires a sufficient large body of water. Due to these limitations it can be concluded that not all testing scenarios are applicable to all scales. To test and asses the semi-full scale and full scale vessels extensively it is recommended to overcome the limitations of the not realizable scenarios, so the full testing method is feasible.

As stated before the testing method provided is based on literature. In this research the testing scenarios are not conducted in reality, therefore there is no proof that all scenarios described in the designed method can be realised. However, since some scenarios are based on testing method of conventional vessels and some are based on already conducted experiments with autonomous vessels it can be stated that for those scenarios there is proof that they are feasible. The remaining scenarios are realistic enough that it is expected that they will be achievable.

The testing method is open to expansion, this can be interpreted in multiple ways. Firstly, more scenarios based on different applications can be designed. There is wide field of possible utilities for autonomous vessels in urban areas. These utilities could be described in scenarios with an objective an added to the method. Also some studies found during the literature survey proposed possible scenarios that were not included due to limitation of the scope. For example this study describes multiple COLREG situations taking place in one scenario [13], this type of combined scenarios have a big potential in an future advanced stadium of the project and could be added. Secondly, the thresholds of some of the KPIs are undetermined. With experience in the field, consulting the right literature and

taking in account the design expectations of an ASV it should be possible to give certain values to the thresholds for the KPIs, so the assessment of the tests directly objectifies the performance. Another option to elaborate the method, is to dig deeper in the measurement methods provided. There are options for different and more accurate measurement methods than the ones described, which will could use different parameters to be measured. The use of another measurement method could result in a better insight of the performance during a test.
Lastly, the way to calculate and asses the KPIs are provided. These formulations could be used to built a automated testing module. These module could be connected to autonomous vessels and directly read out the data from the sensors, so the KPIs could be tracked in real time. This could make the assessment of ASVs faster and makes it appealing to improve the design after gaining insight from the tests.

In chapter 6 the general guideline is used for the AVATAR project and adapted versions are constructed. This shows the practical application of the guideline and how it should be used on different autonomous vessels that require testing. So it is shown that the guideline provided in this research can be a useful tool for assessing the performance of autonomous vessels.

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