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Learning to Swim - How Operational Design Parameters Determine the Grade of Autonomy of Ships

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ABSTRACT: In recent years, ideas and applications for autonomous shipping have been rapidly increasing. In most of today's ship bridge systems decision support systems with different capabilities are installed and officers of the watch rely on them. First tests with fully and constrained autonomous ships are on the way. One of them is the B0 | BZERO project, with the aim of an autonomous 8-hour watch-free bridge, while the ship is still manned. The system's constraints are captured in the operational design domain (ODD) defining all conditions under which the autonomous system can operate safely. We propose the definition of a preliminary ODD considering both regulatory and technical restrictions. Furthermore, we present a new way of defining the level of autonomy of a ship by using the ODD and navigational specifications.

1 INTRODUCTION

Digitalization and automation on ship's bridges are quite common nowadays in the maritime industry. Different systems from electronic charts, automation systems, fuel performance monitoring, or integrated bridge systems up to decision support systems can be found on ships worldwide. In recent years, ideas and applications for autonomous shipping have been rapidly increasing. In most of today's ship bridge systems, decision support systems with different capabilities are installed and officers of the watch rely on them. First tests with fully and constrained autonomous ships are on the way. One of them is the B0 | BZERO project, with the aim of an autonomous 8-hour watch-free bridge, while the ship is still manned. The challenge hereby is the definition and design of the ship's systems.

1.1 *Autonomy Levels*

In the transportation industry, different definitions of autonomy levels exist: Sheridan and ALFUS, SAE autonomy levels, metro grade of automation, National Business Aviation Association levels, Lloyd's Register, Maritime21 [13, 14] or IMO (International Maritime Organization) levels of autonomy [5], whereby the IMO levels (see Figure 1) are the most general and applicable for maritime applications.

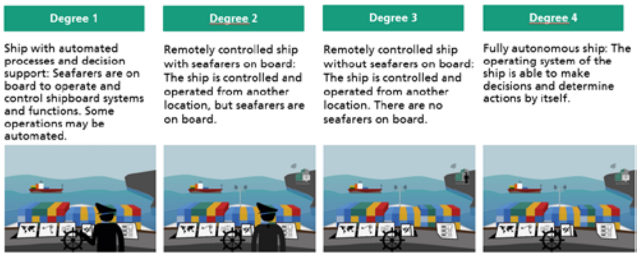

Figure 1. IMO levels of autonomy

The IMO levels of autonomy look at two aspects: On the one hand the manning of the ship and on the other hand the control mode. In level 1 (Decision Support) the ship's crew is still on board, decision support systems and automated processes are available. Shipboard operations are mainly conducted manually, but some may be automated. Level 2 (Remote Control with Seafarers) means that the ship's crew is still on board, but the ship is controlled from another location, whereas local crew is available to intervene if unintended or risky maneuvers or situations apply. The third level (Remote Control without Seafarers) also includes remote control, but here seafarers are not on board. Level 4 (Fully Autonomous) means that no crew is available on board and no remote center is controlling the ship. The shipboard systems are deciding and acting on their own. Nevertheless, and as we will show, there are more sublevels or different combinations of those aspects, and situations where an exact allocation to one of these levels might not be suitable.

1.2 *B ZERO Project*

Looking at recent research, the development of MASS is steadily growing [7]. However, since the era of fully autonomous and commercially viable ships is not yet there, a hybrid approach is developed, where automated and autonomous systems are used, while still the full or a reduced crew is on board. Whilst ship's engine rooms can be already operated without any crew, the ship's bridge still needs to be manned at all times [13]. The project B0 | B ZERO looks into the possibility of using autonomous systems to achieve an 8-hour watch-free bridge. The designed system is intended to be built on an existing ship. Therefore, technical constraints, available sensors and the planned operational area are part of the project's work packages, requiring a thorough planning, specification and limiting of resources, devices and data or information.

1.3 *Aim*

The aim of this paper is to propose a different approach to categorize levels of autonomy for surface ships, after describing the outcomes of the navigational and operational design domain (ODD) of the B0 | B ZERO project. During the process of creating the navigational specifications and the ODD for the B0 | B ZERO project, it became clear that existing autonomy levels are not sufficient to reflect the possible variety of vessel autonomy levels. The need for a further differentiation between more levels of autonomy arose, because the existing IMO levels only focus on the two parameters manning and level of automation of devices. During the B0 | B ZERO project, the necessity for further parametrization occurred, in regards to existing regulations, ship sizes and environmental as well as situational circumstances. Therefore, this paper takes into account a greater variety of parameters influencing the levels of autonomy by considering the findings from the B0 | B ZERO navigational specifications and ODD.

2 METHODS

2.1 *Defining Navigational Specifications*

In order to develop the functional and non-functional specifications of a ship's navigation system for an 8-hour watch-free bridge, a navigational specification was established for the B0 | BZERO project. Those specifications were broken down into fundamental, environmental, human-centered, safety and non-functional requirements.

In a first step the available data sources were summarized, the corresponding navigational domains addressed and gaps and missing data identified. In a second step, the duties of the human officer of the watch (OOW), the autonomous system (referred to as Auto-OOW) and the master, closely derived from human bridge duties, were determined. This means that generally the Auto-OOW will also pass through the four process stages of control [11]: acquisition of information, analysis of information, decision and action selection and action implementation.

As a third step, restrictions concerning the autonomous maneuvering of the system were determined. As a fully autonomous unmanned system desirably would be able to perform in most or any circumstances, some restrictions occur for a system when navigational personnel is included. While defining the restrictions, it was found that setting the margin of possible action restraint will lead to a lower grade of autonomy. Those restrictions were defined in the ODD.

2.2 *Defining the Operational Design Domain*

In order to know under which circumstances the autonomous system can be used, an ODD must be defined. The ODD describes the conditions in which the Auto-OOW can safely navigate autonomously [2, 12]. Conditions could be, for example, low traffic density, good weather, or a sufficient water depth. If the conditions are no longer met, the ODD is left and the system must request human assistance [3] or perform some fallback procedure [15]. A human officer is then called to the bridge to assess the situation and take control if necessary. At higher autonomy levels, the system itself would perform this so-called fallback with the goal of reaching a system state of minimal risk [2]. At the highest autonomy level, i.e., full autonomy, a fallback is not necessary, since the ODD would then be unrestricted [15].

The process of defining the ODD should start early in the design process, as defining the ODD also supports the definition of system and functional requirements [2]. However, the ODD does not only help early in the design process, it also supports evaluating and testing the autonomous system [2]. The ODD can be used to define situations that the autonomous system must handle on its own as well as situations in which it requires human assistance. If the autonomous system does not behave as expected in the corresponding situations, either the ODD must be adapted to be in line with the test results or the autonomous system must be adapted to meet the requirements of the ODD. Therefore, the process of defining the ODD is highly iterative [2].

Finally, the ODD is also employed during autonomous operation in order to monitor the current system state with respect to the ODD. This is referred to as ODD monitoring [2]. Only, when constantly monitoring whether the current conditions are within ODD limits can the system detect possible ODD violations and request human assistance.

2.3 *Methods for gaining the ODD*

The process of defining the ODD was started at the very beginning of the project, as recommended in [2]. As a starting point, a literature search (e.g., [9]) was used to identify conditions potentially limiting the ODD of the Auto-OOW. These conditions are referred to below as ODD factors (see [8]). ODD factors were subsequently adapted and further refined in close exchange with the project partners. The close exchange was particularly important, since it made sure that potential system boundaries were considered as ODD factors right away. It also served to keep all project partners in the loop and to address their goals for the future capabilities of the autonomous system.

For these purposes, N = 6 project partners with nautical (N = 4) and/or technical experience related to autonomous or sensor systems first completed an online questionnaire to further specify ODD factors. The partners with nautical experience possessed on average 14 years of seafaring experience, with two still working as navigators at the time of the survey. The results of the questionnaire were used as a discussion basis in two online workshops with all project partners, which eventually produced a preliminary definition of the ODD and ODD factors. As the ODD is defined and refined iteratively [2], this preliminary version has already been adapted to further project results. The resulting and still preliminary ODD factors are described in detail below. It is expected that the definition of the ODD will be further refined as the project continues.

2.4 *Methods for categorization of autonomy levels*

For a nuanced definition of autonomy levels the outputs and findings of the navigational specifications and the ODD were considered. The fact that a clear definition of autonomy depends also on other aspects besides manning and the location of operation (see IMO levels) arose from the outcomes of the two working packages in the B0 | B ZERO project. A new fragmentation into parameters (conceived from navigational specifications and the ODD) was derived, which were divided into equivalent important sub-parameters.

For each parameter a multidimensional visualization in form of a radar plot (which is also known as web chart or spider chart) was created. To avoid confusion within the nautical profession, the synonym spider chart will be used hereafter. Similar to a probability distribution function, a profile plotted on that spider chart represents the relative distribution measured across more than three comparative sub-parameters, where each sub-parameter is represented by an axis on the chart. With the allocation of a defined value on each sub-parameter axis, a polygon is created by connecting the points. The polygon therefore inherits a definite size, position and shape.

In a further step the spider charts were used as a tool to categorize the three primary parameters into five categories. From the geometrical property of each shape, the areas can be calculated by decomposing the closed polygon into triangles, with the vertices being the (sub)-parameter properties.

Afterwards a closer look onto the distribution of the areas of the developed shapes was taken. As the area of polygons in a spider chart increases almost as a square, rather than linearly, the five categories were derived from a square function and split into the categories, respectively. The resulting area of the shape of each parameter was then used as a categorical value in order to partition the parameters for the level of autonomy (see Figure 2).

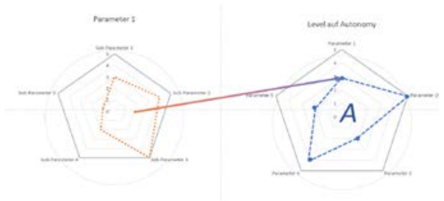

Figure 2. The profile area of a parameter (left) contributing to the level of autonomy (right)

This procedure is not only applied to each parameter, but also to the levels of autonomy. The profile plotted on that chart represents now the relative distribution measured across at least three comparative parameters, where each parameter is represented by an axis on the chart. The so gained shapes provide a first visual impression about each parameter’s influence on the level of autonomy.

3 RESULTS

3.1 *A preliminary ODD for the B0 | BZERO project*

For the preliminary ODD, a total of 15 ODD factors were defined and assigned to the following categories: own ship information, route information, voyage phases, traffic information, weather and system failures. The ODD was defined in terms of its limits (see [2]). When an ODD limit is reached, i.e., when the state of an ODD factor becomes critical, the Auto-OOW requires human assistance. In this case, the human is called to the bridge to gain awareness of the current situation and react to it.

Human support will be necessary, for example, when the Auto-OOW detects a close quarter situation with a target that has the right of way, so the own ship is required to give way. In this case, a close quarter situation was defined by a CPA (closest point of approach) of less than 1.5 NM and a TCPA (time to closest point of approach) of less than 12 minutes to the critical target. If such a situation is detected (the Auto-OOW should prevent this from happening in the first place), a human officer will come to the bridge to have a look at both the situation and the possible maneuvers the Auto-OOW will offer to solve the situation. Either the human will then decide to select one of the suggested maneuvers and the control will remain with the Auto-OOW or the human will take control himself, i.e., the human performs a watch takeover. In other situations, the only option of the human officer will be to take over the watch immediately. For example, if the wind speed exceeds 8 Beaufort, the human must assume control immediately without the option to let the Auto-OOW continue.

These two examples clarify that the ODD factors were divided into two categories based on what reaction is necessary when the factor state is critical: ODD factors requiring immediate watch takeovers and ODD factors where the human OOW decides about who controls the own ship. In the latter case, an evaluation of the human is necessary. Hence, a distinction was made between watch-takeover and evaluation factors. The two ODD factor categories indicate in total three situation states with respect to the ODD. The current situation is either in scope of the ODD (no human response required), out of scope of the ODD (watch takeover required) or unclear and needs to be evaluated (evaluation required). These three states are consistent with the categorization of [3].

Furthermore, it was agreed that the master and selected personnel should have a comparatively high degree of decision-making freedom with regard to ODD limits. Critical values of continuously measurable ODD factors (such as the roll and pitch period, the visibility, the wind speed etc.) should be adjustable by the master and selected personnel, since the definition of which ODD factor conditions are critical highly depends on the ship type and the crew. For example, it depends on the ship type and size, which roll period is to be seen as critical for autonomous operation. The goal, however, is to specify default values for most or all ODD factors.

To account for characteristics of voyage phases that are difficult to measure and to evaluate by the Auto-OOW, we determined that voyage phases should be classified as either autonomy-capable or autonomy-incapable during voyage planning. Then, when entering autonomy-capable voyage phases during the voyage, autonomous operation is feasible, as long as the current situation is also in scope of the ODD. However, autonomous operation is in any case infeasible in voyage phases labelled as autonomy-incapable. Before entering these voyage phases, the Auto-OOW has to hand over the watch to the human officer. Specifically, the following voyage phases should be autonomy-incapable in the project B0 | BZERO: shallow waters, VTS areas, dangerous areas and areas where bad weather is expected. The labels autonomy-capable and autonomy-incapable will be tied to waypoints defined during route planning. Therefore, waypoints are either not ODD relevant, lead to scheduled ODD exits or scheduled ODD entries (if all ODD factors allow the entry).

A summary of all ODD factors and the conditions, in which they are critical to the ODD, as well as the necessary human responses, is displayed in Table 1. For some ODD factors, default critical conditions remain to be defined. For the ODD factor under keel clearance (UKC) as well as for the factor combination CPA and TCPA, two distinct default critical conditions were defined (see Table 1).

3.2 *Categorization of ODD and navigational limitations*

As the restraints of the navigational specifications and the outcomes of the ODD show, several parameters of ship's navigation are affected and influence the grade of autonomy directly. Hence, it seems useful to generally classify those parameters into categories for environment, traffic and own ship (see Table 2).

Table 1. Defined ODD factors with their default critical conditions and required human reactions

category	ODD factor	default critical condition	necessary reaction
own ship information	roll period	to be defined	evaluation
	roll angle	at least 10°	evaluation
	pitch period	to be defined	evaluation
	pitch angle	at least 25°	evaluation
	speed	to be defined	evaluation
	UKC	at most 50m	watch takeover
		at most 0.7 times of the estimated UKC	evaluation
voyage phases	time to autonomy-incapable area	at most 12 minutes	watch takeover
route information	cross track distance	to be defined	evaluation
	deviation between estimated and scheduled arrival time at next waypoint	at least 15 minutes	watch takeover
traffic information	traffic density	heavy traffic (to be defined)	watch takeover
	CPA & TCPA	Target has to give way, CPA at most 1.5 NM and TCPA at most 15 minutes	evaluation
		Own ship has to give way, CPA at most 1.5 NM and TCPA at most 12 minutes	evaluation
	loss of radar targets	loss happens within a radius of at most 12 NM and target AIS data are not available	evaluation
weather	wind force	at least 8 Beaufort	watch takeover
	visibility	at most 3 NM	evaluation
failures	system failure	at least one of the following systems failed: ECDIS, Radar, AIS, gyro compass, echo sounder, GPS, THD, propulsion system, steering gear, alarm system, automatic track control, automatic heading control	watch takeover

Table 2. ODD and navigational parameters

Environment	Traffic	Own Ship Factors
Wave height	Number of ships	Motion (Roll/Pitch)
Wave direction	CPA	Speed
Wind speed	TCPA	UKC
Visibility		Voyage Phase
Time of day		Cross-track distance

Those parameters can be seen as the restraining settings for any autonomous ship. The narrower the range of action or limit for each parameter is set, the lesser the range of possible action is for an autonomous system. Restraining the parameters means to set some boundaries, in which the autonomous system is allowed to freely operate. Each parameter limit thereby has different impacts on the navigation. To illustrate this in more detail and to provide an example, the parameters including their sub-parameters are described further in the following.

3.2.1 *Categorization of Environmental Parameters*

Wave height was named as one restricting sub-parameter for the B0 | BZERO project. As the wave height varies regionally, seasonally and temporarily, a ship might encounter all ranges of wave heights on its voyage. This sub-parameter directly influences the ship's motion and can result in heavy rolling or structural load onto the ship's hull. Additionally, increasing ship motions could cause damage to the cargo, when inappropriately secured. It is anticipated that the wave height is an essential sub-parameter, as an autonomous system needs to react to areas of extreme wave heights, or better to avoid them in the first place. A system needs to monitor the ship's motions, while keeping track using the ship's engines and rudder.

A related sub-parameter is the wave direction relative to the ship. During unfavorable wave directions and periods, the ship can encounter heavy motions, which can have severe consequences both for the crew (when manned) and the ship. Heavy ship motion can lead to severe motion sickness for the crew and to parametric rolling [4] followed by capsizing of the whole ship [16].

Besides wave height and direction, wind speed was also called as one of the sub-parameters, as wind speed can cause damage to cargo and loading. Severe wind speeds in terms of storms and gusts can influence the course-keeping abilities of the ship. Wind speed is directly related to wave height, as the latter is affected and caused by the former and by the time of exposure to those winds [10].

Another important sub-parameter, originating from the COLREGs [6], is visibility, which can be reduced because of fog, dust, sandstorms, heavy rain or snow. Visibility affects which navigation rules apply, since they depend on whether another ship is in sight or not. These human-centered regulations are currently also in force for automated and autonomous ships, although those may be more capable than humans to navigate without optical eye-sight. However, during the B0 | BZERO project that parameter was rated as still to be considered while designing the autonomous system.

Another challenge for automated and autonomous systems is the time of day. The optical representation of a ship during daytime is its silhouette, which can be seen as soon as the ship arrives at the other ship's horizon. The silhouette decreases with fading daylight and at night only the ship's navigational lights are visible. At night, it is more challenging to determine the heading of the other ship and thereby the risk of collision. Similar to visibility, time of day is a very human-centered indicator, and during the project work it was manifested, that the autonomous system has to identify and react to this parameter.

The previously mentioned environmental sub-parameters are split into six sections each and can be seen in Table 3. It can be stated that low range sections restrict the ship's autonomy to a higher degree than upper range sections, whereas upper range sections allow more decision and reaction freedom for the autonomous system. For the sub-parameter time of day, the entries are used twice to cover all six sections due to a shortage of possible options. The environmental restrictions are independent from each other, which means that a heterogenous distribution is possible and expectable. The sections are used as the scale on the vertices of the spider chart.

Table 3. Environmental restriction parameter sections

Scale	Wave height [m]	Wave direction	Wind force [Bft]	Visibility [nm]	Time of day
1	< 2	none	< 2	15+	Day
2	2-4	head	2-4	12-15	Day
3	4-6	bow	4-6	8-12	Twilight
4	6-8	beam	6-8	6-8	Twilight
5	8-10	quartering	8-10	2-6	Night
6	10+	following	10+	0-2	Night

In the following three different random application cases of different restrictions due to environmental sub-parameters are shown in Figure 3 and explained in the following. The vertices (scale of sections) of each sub-parameter in the use cases create a polygon. The smaller the area of the polygon is, the lower the degrees of freedom for the autonomous system are.

Application Case 1. No environmental restrictions apply. The ship system is free to maneuver within all environmental conditions. This means that the ship's system has to be able to navigate in every wave height and direction, at every wind speed, as well as during limited to no visibility and at every time of the day. The area of the polygon is the biggest area in this application case compared to the other two.

Application Case 2. Medium restrictions apply. This application case is taken from the B0 | BZERO project, where a safe maneuvering frame is developed for a real application on a ship. Safe operating limits are determined to be wind speeds up to 8 Bft and wave heights up to 6 m. Wave direction, visibility and daytime are unrestricted. Since in comparison to case 1, wind speed and wave height are restricted, the area of the polygon is smaller indicating a lower overall autonomy level.

Application Case 3. Large restrictions apply. The autonomous system is only entitled to maneuver inside very narrow limits of wind speeds up to 4 Bft, wave heights up to 4 m, and wave directions only from a heading direction. It is also limited to very good visibility (up to 15 nm) and daytime use only. Due to the large restrictions, the area of the polygon is small, indicating very restricted autonomy.

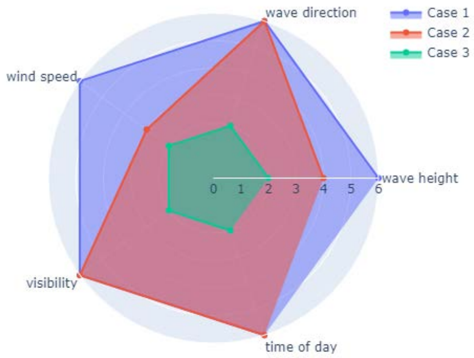

Figure 3. Comparison of three different application cases within environmental restrictions

Away from the three presented application cases, various other cases with varying combinations of environmental restrictions are possible. What one can see in Figure 3 is that with narrowed limits the polygon's area decreases. Expressed in geometry terms this means that the enclosed area A of a polygon P is dependent on the location of the vertices p on each axis. The largest possible area is given in case 1, whereas case 3 only covers a very small area. The environmental restrictions can be summarized into one parameter named "environment" by assigning each polygon size to one of five categories ranging from worst to good (see Table 4). The polygon area size ranges from 2.5 up to 25.

Table 4. Assigning different polygon area sizes to categories representing the overall environmental condition

Area	Category
< 2.5	Worst
2.5 - 4	Bad
4 - 9	Medium
9 - 16	Fair
16 - 25	Good

3.2.2 *Categorization of Traffic Parameters*

A similar categorization as for the environmental parameters was carried out for the traffic and own ship parameters. The three traffic sub-parameters are the number of ships, the CPA- and the TCPA-values (see Table 2). The focus of the selection of traffic parameters lays mainly on the functionalities and capabilities of the autonomous system. The number of ships in the vicinity of the own ship is an indicator of traffic density and was also a limiting factor when it comes to processing power of navigational devices. Within the B0 I BZERO project "heavy traffic" remains to be defined, since its definition depends on the capabilities of the autonomous system. The outcomes of the pending system tests will provide a better insight into these. As a starting point for categorizing different traffic densities, the number of ships within a range of 12 nm (normal optical sight) as displayed in Table 55 will be used. CPA- and TCPA-values were categorized based on standing orders and collision regulations and can also be retrieved from Table 5. Autonomous systems that are able to deal with the smallest CPA and TCPA values have the highest decision making and action freedom. Again, similar to the environmental restrictions the navigational parameters are arbitrary and do not necessarily depend on each other.

Table 5. Navigational parameter sections

Scale	Number of ships within 12 nm	CPA	TCPA
1	< 5	5+ NM	30+ min
2	20	3-5 NM	18-30 min
3	55	2-3 NM	12-18 min
4	115	1-2 NM	6-12 min
5	200+	<1 NM	< 6 min

After traffic parameters were categorized similar to the environmental parameters, the list displayed in Table 6 emerged.

Table 6. Traffic parameter categorization

Area	Category
< 1.5	Low
1.5 – 4	Few
4 - 9	Average
9 - 16	Increased
16 - 25	High

3.2.3 *Own Ship Factors*

Own ship factors were categorized similarly to environmental and traffic parameters (see Table 7). The sub-parameters were motion (roll and pitch), speed, under keel clearance, voyage phase and cross track distance. As the holistic ship's motion is very ship and ship-type specific, roll and pitch angles will be determined. The ship's speed is another sub-parameter which is very ship specific. Therefore, the categorization will not take the absolute speed into account, but the percentage of design speed. Furthermore, the under-keel clearance will not be categorized in absolute meters, but in relation to the draft of each ship. Special attention is paid to the voyage phases, which were determined during the B0 I BZERO project as time slots and areas of a ship's voyage correlating to the passage planning. Here, the categories were chosen as follows: The least degree of freedom is assumed, when the ship is only allowed to navigate in declared areas. Further decision-making scope is achieved by allowing the ship to navigate during sea-passage up to the highest level of freedom, the berthing. The higher level of a voyage phase does always include also the lower levels, i.e., a ship that can manage fairways autonomously (section 4) will also be able to manage sea passages autonomously (section 3). The cross-track error will also not be categorized in absolute numbers, but in relation to the ship's length.

Table 7. Own ship sub-parameter sections

Scale	Roll/ Pitch Angle	Speed [% of design speed, kn]	UKC [m perm draft]	Voyage phase	XTD [m perm LOA]
1	2°/5°	70-80	32+	Declared areas	20+
2	10°/20°	50-85	16	Sea passage	10
3	25°/30°	40-90	8	Fairways	5
4	40°/50°	20-95	4	Pilotage	2
5	40°+/50°+	0-100	< 2	Berthing	< 1

The categorization of own ship factors based on the polygonal areas leads to the categories displayed in Table 8.

Table 8. Categorization of own ship factors

Area	Category
< 1	Most restricted
1 - 4	Heavily restricted
4 - 9	Moderately restricted
9 - 16	Less restricted
16 - 25	Least restricted

3.3 *Level of autonomy*

Looking into the restrictions by the explained categories and the aspects of autonomy stated in section 1.1 it is clear that a combination of them lead to different levels of autonomy. Therefore, a categorization of inputs is conducted and for different constraints the outcomes can be seen in Table 9.

A last step for a new declaration of levels of autonomy is the categorization of the in Table 9 assigned parameters according to the polygon area, using the aforementioned approach. That means that possible polygon areas are divided into categories according to a square function. In detail the results can be seen in Table 9.

Table 9. Proposed autonomy levels

Area	Level of autonomy
< 2.5	Assistance
2.5 - 4	Partial Automation
4 - 9	Conditional Autonomy
9 - 16	High Autonomy
16 - 25	Full Autonomy

The lowest level of autonomy within this framework is called "Assistance", as it has similar characteristics as a decision support system. It can be seen that the lowest possible parameter categories are used, which means the least possible freedom for the navigational systems and still manning on the ship, which makes it a support system. Within partial automation, conditional and high autonomy, some parameters are set to an advanced level giving the autonomous system more degrees of freedom. As this model proposes a free distribution of the parameters, it is not precisely defined which parameter lead to one of those levels. Different combinations are possible, as it can be seen from the autonomy application cases (see Figure 4). Although some application cases seem to have a large degree of decision freedom, singular restriction narrows the end result. That leads to the fact, that the application cases green and yellow fall into the category conditional autonomy and the application cases purple and red fall into the high autonomy level. In the full autonomy level, the parameters are nearly set to full degree of freedom and the autonomous system is free to maneuver at almost any circumstance.

3.4 *Use Cases*

For the demonstration of use cases, the parameters are arbitrary. In Figure 4, five different use cases are shown. It can be seen that the restriction of parameters reduces the polygon area, leading to a lesser level of autonomy. The applications were taken from realistic nautical conceivable situations, shortly described in Table 11.

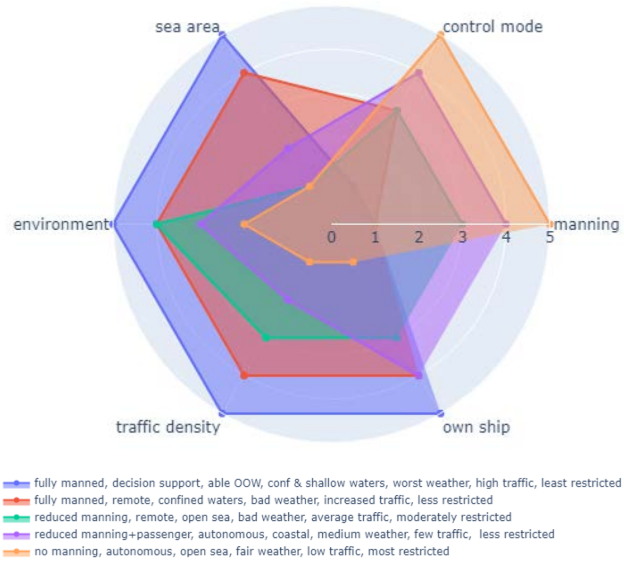

Figure 4. Comparison of different autonomy application cases

Table 10. Parameters for level of autonomy

Scale	Manning	Control mode	Sea area	Environment	Traffic density	Own ship factors
1	Fully manned on duty	Local control	Open sea	Good	Low	Most Restricted
2	Fully manned off duty	Local supervision	Coastal	Fair	Few	Heavily Restricted
3	Reduced manning off duty	Remote control	Traffic separation schemes	Medium	Average	Moderately restricted
4	Reduced/no manning, but passengers on board	Autonomous supervision	Confined waters	Bad	Increased	Less Restricted
5	No manning	Autonomous control	Confined & shallow waters	Worst	High	Least Restricted

Table 11. Application situation for autonomy level presentation

	Manning	Control mode	Sea area	Environment	Traffic density	Own ship factors
Blue	Fully	Decision support system with able human OOW	Confined and shallow waters	Worst	High	Least restricted
Red	Fully	Remote	Confined waters	Bad	Increased	Less restricted
Green	Reduced	Remote	Open sea	Bad	Average	Moderately restricted
Purple	Reduced manning + passengers	Autonomous	Coastal	Medium	Few	Less restricted
Yellow	No manning	Autonomous	Open sea	Fair	Low	Most restricted

4 DISCUSSION

Commercially viable fully autonomous ships are rather unrealistic in the near future [1]. Therefore, some form of constrained autonomy, as in the B0 | BZERO project, is pursued. The project aims at developing a constrained autonomous system that can handle most situations autonomously, while it still requires human assistance on the bridge when certain situations are encountered. To know exactly when human assistance is required, an ODD and navigational specifications must be defined and specified. The aim of this paper was twofold. First, we wanted to provide a preliminary definition of the ODD and navigational specifications of a constrained autonomous vessel using the B0 | BZERO project as an example. Second, we aimed at providing a categorization of important parameters that need to be considered when evaluating a vessel's autonomy based on our defined ODD and navigational specifications.

As our defined ODD and navigational specifications show, several parameters must be considered when determining the exact manifestation of a vessel's autonomy. The parameters can be divided into several categories and can take on various values and forms. Our categorization makes it possible to flexibly select which values and forms lie within the ODD and which do not. The more possible parameter values and forms are included in the ODD, the higher the degree of the ship's autonomy. Due to the high flexibility of the categorizations, the degree of autonomy can be tailored to specific ship conditions, to the needs of a shipping company and to any system limitations. The parameters' values and forms selected for the ODD can also subsequently be used to develop scenarios to test the performance of the selected degree of autonomy [2]. Such tests also provide insights into which parameters need to be adjusted and to what extent.

It remains to be tested, in general, how the ODD proves itself in practice. Currently, the defined ODD is still very strongly oriented towards human capabilities and less towards system boundaries. By conducting more tests with the help of the defined scenarios, the focus could shift more towards system boundaries. Furthermore, individual ODD factors such as heavy traffic or critical values for the roll and pitch period remain to be defined. For certain ODD factors such as visibility, it is not yet clear, how they can be measured. Another limitation of the ODD is that the human still possesses considerable decision-making freedom. The human, for example, is responsible for classifying voyage phases either as autonomy-capable or autonomy-incapable during voyage planning. The high degree of decision making freedom is accompanied by a high degree of human responsibility and allows room for human error [1].

Furthermore, it is proposed to define the levels of autonomy of a ship based on the limitations of the parameters manning, control mode, sea area, environment, traffic density and own ship restrictions. The visualizations have shown that is possible to derive a categorization of autonomy levels with a further segmentation of parameters and sub-parameters. Nevertheless, further application cases as well as further segmentation and parameter description might lead to different categories and results. Limits also occur in the description of wave height e.g., as monster waves might be experienced. That leaves also the discussion open for using limitations for some parameters, as they might be exceeded or undercut. Further criticism can be directed towards the arbitrary combination of parameters, as some are not totally free combinable, as "no manning" with "decision support systems".

Another set-back of that system is the composition of parameters. As the model is designed to use only the area of the created polygons, it is no longer possible to infer the exact degrees of freedom for the individual parameters from the area. The same occurs during the specification of parameter's degrees of freedom via specifying the sub-parameters. That is why a continuously moderate level of sub-parameters would obtain the same level of autonomy as a combination of high- and low-level sub-parameters.

5 CONCLUSIONS

In this paper the approach of defining the operational design domain for an autonomous navigation system is presented. Together with the outcomes of the navigational specifications of the B0 | BZERO project a new system for the determination of the level of autonomy is proposed. The theoretical framework behind our approach relies on the elaboration of ODD parameters for the use case of an 8-hour unmanned bridge as well as on the fact that the data on spider charts create polygon shapes allowing to measure multidimensional performance as well as categorizing of parameters. Applying this approach shows a wider spread of distributing parameters to the levels of autonomy than in the IMO model, as well as the opportunity to determine already the level of autonomy of a ship in the early stage of specification of the systems. Until now, this paper serves as theoretical foundation, the practical use has to be shown in the future and it has to prove its potential.

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