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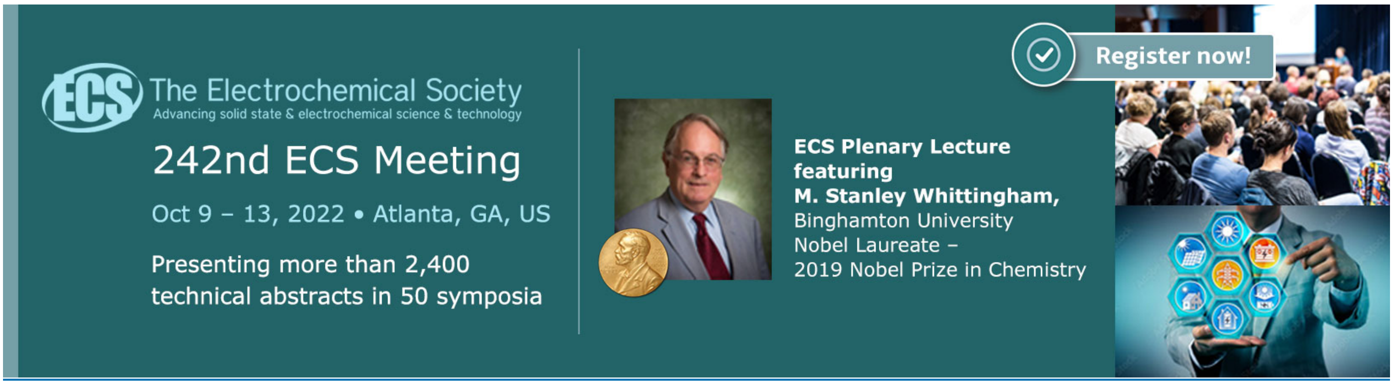

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Levels of autonomy for ships

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Abstract. This paper gives a summary of previously published papers on the definition of autonomy for ships, how this relates to different crewing regimes, and the terminology to be used. A conclusion is that autonomy should be retained as a descriptive term, but that we should distinguish between "full autonomy" and "constrained autonomy", where the latter is the more relevant term for ships today. The proposed classification of autonomy is related to both degree of automation and degree of human control and will be presented as a matrix with generic classes of autonomy. This matrix is also transformed to a set of more practically useful levels of autonomy based on likely organization of crew on land or on the ship. The paper has mainly been written based on our work with maritime autonomous surface ships (MASS) but is also applicable to other types of surface vessels, e.g. inland waterway vessels.

1. Introduction

Self-guiding mobile robots have a long history and one of the first examples was developed as early as in the 1950's [1], although the term "autonomous" was not used in that paper. The term "autonomous robot" seems to appear around the 1970's [2] and one can assume that the discussions on the meaning of autonomy in the context of robotics started soon after. This discussion is ongoing, and the current proposal in the car industry is to depreciate the term "autonomous" and use "driving automation systems" instead [3]. Section 2 will give some background to this discussion and provide a rationale for continuing to use the term "autonomous ship". This includes a more detailed definition of both automation and autonomy in the context of ships.

The next point that often cause confusion is the relationship between ship autonomy and crew presence, either on the ship itself or in a remote control center (RCC). Section 3 explains why human oversight will be necessary for many years to come. Different combinations of crew attendance on the ship or in the RCC, and the corresponding required capabilities in the automation system will be classified. The term "operational envelope" will also be explained as an alternative to the corresponding term "Operational Design Domain" in the car industry.

The final subject that will be discussed is the levels or degrees of autonomy. Section 4 will propose a classification scheme, which includes the concept of "constrained autonomy". This refers to a combination of automation and human intervention that overcomes some of the problems related to a safe human-automation interface. This classification scheme will also be developed into a list of more application-oriented levels of autonomy.

Section 5 gives a brief example of assignment of autonomy levels and section 6 provides a summary of conclusions and a brief outlook on further research.

2. Autonomous or automated?

Autonomy versus automation has been discussed extensively in the literature and many different proposals have been made for definitions of both terms [4].

The word "autonomy" is derived from the Greek word "autonomia" which means independent, or more literally, living by one's own laws [5]. In engineering, the term has been used to describe the ability of an engineering system to make its own decisions, without the need for the involvement of an exogenous system or operator [6]. However, this is in practical terms indistinguishable from the definition of automation: "pertaining to a process or equipment that, under specified conditions functions without human intervention" [7]. Several authors have suggested additional criteria to distinguish automation from autonomy, but there are weaknesses with many of these approaches [4].

The ambiguity of the terms has led the car industry, represented by the Society of Automotive Engineers [3] and the British Centre for Connected & Autonomous Vehicles [8], to suggest that the term "driving automation" should be used instead of autonomy. On the other hand, the International Maritime Organization (IMO) uses the term autonomous, as e.g. in "Maritime Autonomous Surface Ships" (MASS). The inland waterway community, represented by the Central Commission for the Navigation of the Rhine (CCNR), follows the SAE example, and refers to "levels of automation" [9].

In [4] it is concluded that autonomy as a term is indeed relevant for ships and that it is possible to provide definitions that clarify the distinction between automation and autonomy. An important argument in favor of this is that "autonomy" is already being used extensively, e.g. by IMO and the maritime industry. Furthermore, the term autonomy can be used to describe ship automation functions that requires a new approach to approval because it:

1. Implements automated control and monitoring responsibilities that are today allocated solely to humans and where specialist training is required as, e.g. specified in the STCW code [10].
2. Is designed to operate safely without human supervision for certain periods or under certain circumstances, which is not allowed today.

As automation already is common on ships and inland vessels, e.g. as autopilots or engine automation, it is necessary to define the basic difference between today's automation and autonomy. The main points to consider are:

1. Ships needs many different processes to function, e.g. energy production, stability, fire safety and navigation. Not all need to have the same level of autonomy.
2. Ship processes can have different levels of autonomy during different voyage phases, e.g. open sea versus port navigation or lock passing.
3. As will be discussed in section 3, it is highly likely that autonomous ships will be supervised by humans. These humans may be onboard or in the RCC, so autonomy does not imply that the ship needs to be uncrewed.

In the context of autonomous ships, the following definition of automatic has been developed by ISO [11]: "*process or equipment that, under specified conditions, can function without human control.*" This says that automation can control the relevant process, but it may not be allowed or approved to do so, without continuous supervision. This can be exemplified by an autopilot that safely can steer the ship for hours or days, as long as there is a human present, that can disable the autopilot to take evasive manoeuvres, when necessary.

Arguably, the most significant change from today's automation to autonomous operation is that autonomous processes must be approved to be operated without human supervision or intervention. This has led to the following definition for autonomy: "*In the context of ships, autonomy means that one or more of a ship system's processes or equipment, under certain conditions, is designed and verified to be controlled by automation, without human assistance*"[11]. They key phrase here is designed and verified to emphasize the need for formal approval of the automation system to operate without human supervision or control.

3. Uncrewed, remote controlled, or automated ship?

In popular literature, autonomous ships evoke idea of ships sailing completely without human control and with no crew, neither onboard nor in the RCC. In reality, the picture is much more complex. None of the known MASS projects aim for full autonomy today. Although many are aiming for uncrewed operation of the ships, all will use an RCC for supervision.

The reasons for this are usually the result of a cost-benefit assessment [12]:

1. Ships are few, large, and expensive, and the relative cost of using an RCC is small compared, e.g. to that of an autonomous car.
2. The high value of the asset as well as potentially severe consequences from any accidents, will make owners very reluctant to leave them unsupervised.
3. Sensors and object classification can in principle be developed to an arbitrary high reliability, but at a cost. Once the RCC is in place, it will be more cost-effective to use the operators to handle the rare and difficult cases.

However, there are also reasons why automation may not be able to handle all problems [13]:

4. In encounters with crewed ships, it will be very challenging, if not impossible, to develop automation that sufficiently well can predict what the other ship will do in all situations. Until new regulation and technology is developed, a human is in most cases needed to handle situations that are outside the automation's capabilities.

Furthermore, ships move relatively slowly, and often in open and uncongested waters. In such cases, difficult situations can be detected in time for a human operator to be alerted to the need for intervention, and to allow the operator to get sufficient situational awareness to take a safe action to avoid or correct the situation. The general operating conditions also mean that the need for intervention is a relatively rare occurrence. This means that a team of RCC operators can operate more than one ship each. In the MUNIN project, experiments indicated that one operator can supervise six ships [14], but this requires a specialized expert team that can take over control in situations that are too complex or time-consuming for the first-line operators.

Some important benefits of uncrewed ships are increased cargo capacity, capital cost savings, and energy saving from removing the accommodation section [15]. This benefit is obviously relatively larger the smaller the ship is. For large ships, the benefit will be small, so autonomous ship projects seen today are all related to small ships on shorter voyages. Also, on today's larger ships with long voyage durations, crew sizes are probably near the minimum needed to operate and maintain technical systems onboard. Thus, autonomy on larger ships is more likely to be used for decision support, to increase safety, or to allow crew to go to sleep during night-time passages in open sea. Also in these cases, one may want to have an RCC as backup.

This means that there are several combinations of onboard automation, onboard crew, and supervision from RCC that are likely. This is shown by the four rows in Table 1, where respectively automation and/or RCC are used to implement some of the responsibilities that today are handled by the crew. The columns represent different variants of the crew onboard the ship: **Full** is a full normal crew. **Periodically** is crew that can be away from control positions for some time, e.g. when sleeping during night. **Uncrewed** is no crew on the ship at all. Note that the latter may also include the case where there are safety personnel and/or passengers onboard that do not control the normal ship processes, but can be involved, e.g. in passenger safety functions.

Table 1. Onboard crew cooperating with automation and RCC

	Full	**Periodically**	**Uncrewed**
Automation	AO	CA	FA
Automation & RCC	AO & RS	CA	CA
RCC	RS	RC	RC
Crew only	As today	-	-

The codes in the table cells show the most likely operating modes:

- **RS:** Remote supervision from RCC, crew in charge.
- **AO**: Automatic operation of some processes, but crew in charge at all times.
- **RC**: Remote control from RCC, RCC in charge.
- **CA**: Constrained autonomous, crew, RCC, and automation share responsibilities. RCC is needed when the crew is not at the control position.
- **FA**: Fully autonomous. No crew neither on the ship nor in RCC.

These codes are further explained in section 4.

Note that there are other, less likely, operating modes for most combinations that have been omitted from the table, e.g. that RCC do remote control also for a fully crewed ship.

As was discussed above, it can be assumed that very few ships will be fully autonomous. Thus, control of autonomous ships will be a shared responsibility between automation and humans, and the design of the human-automation interface will be an important factor. This is common to a range of other types of "Industrial Autonomous Mobile Robots" (IAMR) that operate in controlled or semi-controlled environments, such as autonomous mining trucks and automatic guided vehicles [16].

The car industry has other challenges. For cost reasons, they cannot easily rely on an RCC, and the high speed of cars and the complexity of the environment makes it difficult to safely hand control over from automation to human if something unexpected happens. This segment has defined the concept of the operational design domain (ODD) as the "*operating conditions under which a given driving automation system or feature thereof is specifically designed to function*"[3],[8]. For the higher automation degrees (3 to 5) defined by SAE, the automation is expected to handle the full ODD. For levels 3 and 4 the ODD is limited, and the driver must handle situations outside the ODD. The driver must also be able to act as a fallback on level 3 if the automation system fails. There have been some discussions on whether this type of interaction between automation and human is safe [17], and this is one reason why it has been proposed that ships may need an alternative to the ODD, which has been called the "operational envelope" [12].

Another reason to use an operational envelope instead of ODD is that autonomous ships almost always will use a combination of automation and human control. Thus, the operational envelope is defined as "*conditions and related operator control modes under which an autonomous ship system is designed to operate, including all tolerable events*", where "autonomous ship system" is defined as "*all elements that interact to ensure effective functioning of the autonomous and non-autonomous processes and equipment that are necessary to perform the ship's operation or voyage*" [11].

The definition of the operational envelope also requires a definition of a fallback state which is a "*designed state that can be entered through a fallback function when it is not possible for the autonomous ship system to stay within the operational envelope*".

This allows an integrated description of automation and crew responsibilities in the different situations the ship is designed to encounter [12]. Developments are also underway to find methods where these concepts can be integrated in a more formal description of autonomous ship system capabilities and how this can be used in approval [18].

4. How to define levels of autonomy?

There are at least as many proposals for *levels* of autonomy as there are definitions of autonomy [19]. This section will use the definition of autonomy as presented in section 2, and the interaction between human and automation as discussed in section 3 to describe a general classification scheme for ship autonomy. More details, and the background for the description, can be found in [12].

The classification scheme is based on four degrees of respectively automation and human control, as shown in Table 2 on the next page.

The degree of human control describes the level of attention that the operator is giving to the operation at hand and is specified as the maximum time the operator needs to reach the control position, gain situational awareness and be ready to perform actions to maintain safety (T_{MR} – maximum response time).

The degree of automation describes the automation systems ability to be in control of a given operation, and to maintain safety for a specified future time (T_{DL} - response deadline), without any human assistance.

Table 2. Degrees of automation and human control

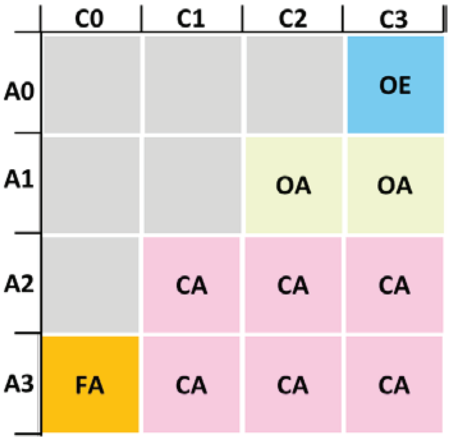
Degree	Automation	Human control
0	Low, $T_{DL} \approx 0$	None, $T_{MR} = \infty$
1	Partial, $T_{DL} > 0$	Available, $T_{MR} >\approx 20\text{min}$
2	Constrained, $T_{DL} > t$	Discontinuous, $T_{MR} >\approx 1\text{min}$
3	Full, $T_{DL} = \infty$	Continuous, $T_{MR} \approx 0$

The main idea behind **constrained** automation is that even if human intervention is sporadically needed, this can be made much safer and operator friendly if the automation system is able to issue an alert before an action by the operator may be needed. This requires that the automation system can determine T_{DL}, which in turn requires that the capabilities of the automation system is well defined, and possibly constrained to functions where T_{DL} can be reliably measured. When this is combined in a system where the automation system also knows the operators' maximum response time T_{MR}, the automation can issue an alert when $T_{DL} \leq T_{MR}$. This type of cooperation between human and automation is called *constrained autonomy* [18]. An example of how this could work is that the automation system has a limited set of pre-defined operator modes, each associated with a known T_{MR}. Some examples with the corresponding human control mode from Table 2 in parenthesis could be "on bridge, in control" (Continuous), "on bridge, not supervising" (Discontinuous), or "not on bridge, sleeping" (Available).

Partial automation also has a non-zero T_{DL} but differs from constrained automation in that T_{DL} cannot be determined by the automation system. This makes it impossible to issue an alert to the operators. Operators can still use their own judgement as to if, and for how long, they can leave the control position, but still need to return often enough to ensure that the ship is still safe. This puts additional strain on the operators and makes it impossible, e.g. to allow operators to go to sleep during nigh.

The actual value of T_{MR} will depend on the organization of the RCC and the crew. There are many cases where it is useful to use more or fewer categories for T_{MR} than shown in Table 2.

The categorization used in Table 2 allows the definition of four useful classes of human-automation interfaces as illustrated in Figure 1. Here columns represent human control degrees and rows automation degrees. The unlabeled cells represent combinations that cannot be sustained.



	C0	C1	C2	C3
A0				OE
A1			OA	OA
A2		CA	CA	CA
A3	FA	CA	CA	CA

Figure 1. General classification of operations

The labeled cells represent four different classes of viable human-automation interfaces:

- **OE** (Operator Exclusive): Limited automation, operator must be always present.

- **OA** (Operator and Automation): Automation can control the system, but with continuous attention from the crew. The crew must use their own judgement as to how far away from the control position they can be.
- **CA** (Constrained Autonomy): Automation can control the process for a known period without human attention. The human will be alerted in time to get safely back to control, when needed.
- **FA** (Full Autonomy): Automation can control the process for as long as needed without human attention.

This diagram is independent of if crew are in an RCC or on the ship, but one would assume that C1 is the most useful for onboard crew, while C2 may be most appropriate for RCC. Note that FA could have been used in the whole bottom row. However, as humans are in a monitoring or control function for C1 to C3, these are classified as CA.

This classification scheme provides a systematic and unambiguous definition of how humans and automation interact, e.g. for use in system documentation and approval. It may, however, be less useful in describing the actual implementation of automation in a specific autonomous ship system. This will require more details on the definition of time constants T_{MR} and T_{DL}, and how the RCC and onboard crew are organized. For this purpose, one may want to use a more descriptive scale. Several different methods have been proposed as the basis for such a scale [19] but here we will briefly describe a scale based on the one proposed by the Norwegian Forum for Autonomous Ships [20]. This tries to catch the most relevant combinations of automation and human control, which could be called levels of autonomy. Each level has got an abbreviated form as well as a full name and the code in parenthesis corresponds to the autonomy class codes used in Fig. 1:

- **DC: Direct control** (OE): This is the situation on ships today where the crew has full control of the ship and uses relatively simple automation and decision support functions.
- **AO: Automatic operation** (OA): Examples of this could be dynamic positioning, automatic berthing, or automatic crossings where automation performs operations under continuous supervision.
- **RS: Remote supervision** (OE/OA): A ship with conventional crew, and with DC or AO autonomy level onboard, is continuously supervised from shore, e.g. for increased safety.
- **RC: Remote control** (OA): In this case the ship would be remotely controlled from shore, either all the time or, e.g. during night time. This normally uses the AO autonomy class, as OE is more work intensive for the RCC operators, and one will want to avoid this, if possible.
- **PU: Periodically unattended** (CA): The ship can steer itself automatically for extended periods, e.g. in open waters and calm weather. Crew is available onboard to handle more complex situations, but can be away from the controls and, possibly at sleep during nighttime.
- **CA: Constrained autonomous** (CA): Uncrewed operation with constrained autonomy onboard but with operators in RCC that can handle more complex situations. This corresponds to PU onboard.
- **FA: Fully autonomous** (FA): The ship handles all foreseeable situations by itself and there is no crew neither on ship nor in RCC. This is not very realistic today, except in very simple cases.

There are many more combinations, but the above examples are the most relevant today, as one will normally optimize the ship and RCC crew responsibilities to the capabilities of the automation system.

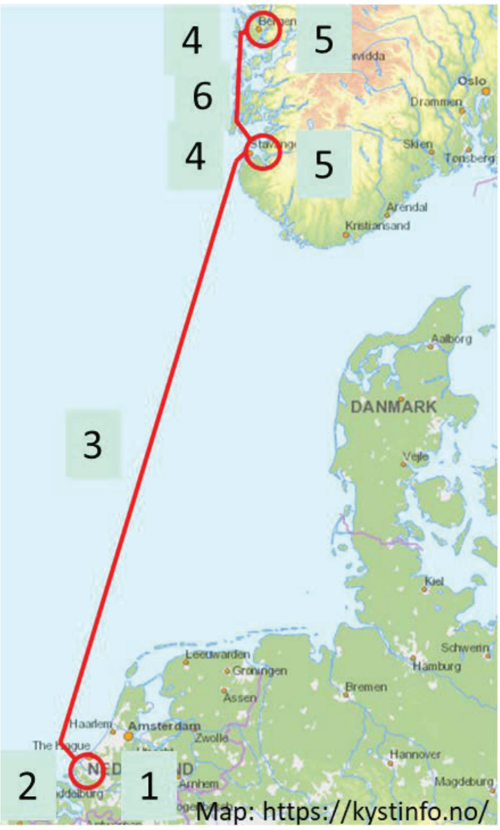
5. An example

To illustrate the concepts described in the previous section, we will look at a hypothetical example: A container feeder vessel trading between the cities Stavanger and Bergen on the west coast of Norway, and Rotterdam in the Netherlands. The voyage is illustrated in Figure 2.

The labels show a simplification to six general operations or voyage phases:

1. Port operations in Rotterdam, including movement between terminals, cargo operations etc.
2. Departure from or arrival to port area Rotterdam, possibly including e.g. waiting or anchorage.

3. Open sea passage.
4. Arrival to or departure from Stavanger or Bergen, relatively small ports with limited traffic.
5. Port operations in Stavanger or Bergen.
6. Sheltered water transit between Bergen and Stavanger. Some narrow passages and significant local traffic.



Map: https://kystinfo.no/

Figure 2. Example route

We can then consider two realizations of this example. One is a crewed vessel where autonomous control is used onboard to assist crew and to allow them to go to sleep during sea passage at night-time. The second is an uncrewed ship with supervision from a continuously manned RCC.

Table 3 shows an example of likely levels of autonomy for three different function groups through the six voyage phases and for the two different crewing options. The leftmost column shows the voyage phases (VP). To the right of that are two groups of three different functions for respectively the crewed ship and the RCC controlled ship. The three function groups are **stability**, e.g. ballasting, water ingress and stability monitoring; **energy**, e.g. main and auxiliary engine operations; and **navigation**, e.g. outlook, position fixing and maneuvering. The cells are labeled with the level of autonomy as suggested at the end of section 5. The shaded cells indicate where constrained autonomy can be used, which corresponds to PU (periodically unattended) for the crewed ship and CA (constrained autonomous) for the RCC operated ship.

On the crewed ship, stability will probably be automated, but supervised during port operations, and using constrained autonomy otherwise. Energy production will likely be using constrained autonomy in all phases. However, dependent on the type of cargo handling equipment, it may be on a lower level during port operations. Navigation will use constrained autonomy during the deep-sea passage. Here, traffic is relatively low and ships far apart and easy to detect on radar. Thus, the automation systems can take care of most situations and have time to alert a sleeping crew if the situation becomes difficult. In ports one probably wants to use direct control and in sheltered transit crew supervised automatic operation.

Table 3: Autonomy levels

	Crew sleeping, $T_{MR} \approx 20$ minutes			RCC operators, $T_{MR} \approx 1$ minute		
VP	**Stability**	**Energy**	**Navigation**	**Stability**	**Energy**	**Navigation**
1	AO	PU	DC	RC	CA	RC
2	PU	PU	AO	CA	CA	CA
3	PU	PU	PU	CA	CA	CA
4	PU	PU	AO	CA	CA	CA
5	AO	PU	DC	RC	CA	RC
6	PU	PU	AO	CA	CA	CA

On the RCC controlled ship, the automation degrees are similar, although the autonomy levels have different names.

An important difference between crewed and RCC operations is that all navigation phases are moved to a higher automation degree when the RCC in charge. The more extensive use of constrained autonomy is possible because the RCC crew will have a lower T_{MR} than a sleeping crew. This means that automation can be relied on in more operations, as human assistance is more easily available. The operations inside the port will also generally need a higher automation level (AO) than for the crewed ship (OE). This is to keep the workload for the RCC operators at a reasonable level.

Note that this example does not consider need for technical maintenance, equipment interventions, or similar issues.

6. Summary and conclusions

Autonomy and autonomy levels are being discussed in many different transport modes, where ships belong to the group of "industrial autonomous mobile robots". Ships are characterized by being large, expensive, and slow moving in environments with relatively little traffic. For this reason, autonomous ships will normally have humans involved in the control of the ship. This means that it is more important to focus on the effective cooperation between humans and automation, rather than on creating automation that can control the ship fully independent of humans.

The car is very different: Cars operate in very complex environments at high speeds, and the main target is fully automatic control. While the car industry uses the ODD as the format for describing the automation system's capabilities, it is proposed to use the "operational envelope" for autonomous ship systems, where also human responsibilities are included in the envelope.

As was discussed in section 2, the term autonomy is a useful concept when applied to ships, but it must be given a very clear definition to distinguish it from automation. Our proposal is to base the differentiation on whether the automation is *designed and verified* to operate without human assistance. However, this raises a new question: How do you design and verify automation to qualify as autonomous? One possibility is to aim for a *constrained* autonomous system. This means that functionality is limited to that which the automation system can reliably assess in terms of complexity related to its own capabilities. By careful design, this will allow the automation system to alert the operator in time to take over control, when complexity is about to exceed capabilities.

Constrained autonomy can be used to construct a cooperative human-automation system, where the human is warned about situations where intervention may be needed. This avoids that the human continuously must monitor the ship and its environment to detect any developing problem. This, in turn, allows us to build complete systems with automation, onboard crew, and RCC crew that effectively and safely can control autonomous ships.

SINTEF Ocean is currently engaged in several research projects that are testing out the concepts of the operational envelope and constrained autonomy on a selection of use cases. These projects are also investigating how UML (Unified Modelling Language) can be used to capture the ideas of the operational envelope and the different classes of autonomy in a more formal way than, e.g. the "concept of operation" (CONOPS) that is being suggested as the basis for approval by several classification societies and administrations [18].

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References

[1] Walter, W. G. (1951). A machine that learns. Scientific American, 185(2), 60-64.
[2] Fu, K. (1971). Learning control systems and intelligent control systems: An intersection of artificial intelligence and automatic control. IEEE Transactions on Automatic Control, 16(1),

70-72.
[3] SAE J3016 (2021) Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems, Ed. 2. SAE International.
[4] Rødseth, Ø. J., & Vagia, M. (2020, November). A taxonomy for autonomy in industrial autonomous mobile robots including autonomous merchant ships. In IOP conference series: materials science and engineering (Vol. 929, No. 1, p. 012003). IOP Publishing.
[5] Online (2022), Online Etymology Dictionary, Retrieved January 2022 from https://www.etymonline.com.
[6] Albus, J., Antsaklis, P., Meystel, A., Passino, K., Samad, T. (1998). Setting the stage: some autonomous thoughts on autonomy. In: IEEE ISIC/CIRA/ISAS Joint Conference.
[7] IEC (2013) IEC 60050-351, International Electrotechnical Vocabulary - Part 351: Control Technology.
[8] BSI (2020), BSI PAS 1883:2020 – Operational Design Domain (ODD) taxonomy for an automated driving system (ADS) – Specification, The British Standards Institution 2020.
[9] CCNR, Automated Navigation – Definitions of levels of automation in inland navigation, Resolution 2018-II-16.
[10] IMO (1978), International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978 – as amended.
[11] ISO (2022), ISO/PRF TS 23860, Ships and marine technology – Vocabulary related to autonomous ship systems, Final text for proof-reading.
[12] Rødseth, Ø.J., Nordahl, H., Wennersberg, L.A.L, Myhre, B., Petersen, P. (2021) Operational Design Domain for Cars versus Operational Envelope for Ships: Handling Human Capabilities and Fallbacks, Proceedings of the 31st European Safety and Reliability Conference, ISBN 9789811820168.
[13] Rødseth, Ø.J., Wennersberg, L.A.L, Nordahl, H. (2021), Improving safety of interactions between conventional and autonomous ships, Proceedings of the 1st International Conference on the Stability and Safety of Ships and Ocean Vehicles, 7-11 June 2021, Glasgow, Scotland, UK.
[14] MacKinnon, S.N, Man, Y., Baldauf, M. (2015), Final Report: Shore Control Centre, MUNIN Deliverable D8.8. URL: http://www.unmanned-ship.org/munin/news-information/downloads-information -material/munin-deliverables/ (accessed January 2022).
[15] Kretschmann, L., Burmeister, H. C., & Jahn, C. (2017). Analyzing the economic benefit of unmanned autonomous ships: An exploratory cost-comparison between an autonomous and a conventional bulk carrier. Research in transportation business & management, 25.
[16] Vagia, M., & Rødseth, Ø. J. (2019). A taxonomy for autonomous vehicles for different transportation modes. In Journal of Physics: Conference Series (Vol. 1357, No. 1, p. 012022). IOP Publishing.
[17] Inagaki, T., & Sheridan, T. B. (2019). A critique of the SAE conditional driving automation definition, and analyses of options for improvement. Cognition, technology & work, 21(4), 569-578.
[18] Rødseth, Ø. J., Wennersberg, L. A. L., & Nordahl, H. (2021). Towards approval of autonomous ship systems by their operational envelope. Journal of Marine Science and Technology.
[19] Vagia, M., Transeth, A.A. and Fjerdingen, S.A., (2016). A literature review on the levels of automation during the years. What are the different taxonomies that have been proposed? Applied ergonomics, 53, pp.190-202.
[20] Rødseth, Ø. J., & Nordahl, H. Ed. (2017, October). Definitions for autonomous merchant ships. Norwegian Forum for Autonomous Ships, Version 1.