Meaningful Human Control in Autonomous Shipping: An Overview

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Abstract. This paper presents an overview of the aspects related to meaningful human control in autonomous shipping. Autonomy is described as a multi-faceted construct including self-sufficiency and self-directedness, which are related to a range of conditions a ship can deal with. This means that autonomy levels will vary in different operational situations. As a consequence, active operator involvement and workload will fluctuate and will sometimes be unpredictable. In case of supervising multiple ships, it is not feasible to maintain a minimal level of situation awareness of all the ships. In order to facilitate operator situation awareness recovery and other human-automation collaboration principles an Intelligent Operator Support System concept is outlined. Whether the large-scale application of Maritime Autonomous Surface Ships will provide equivalent safety and resilience levels will largely depend on the intelligence of the onboard control systems, the design quality of the human-autonomy collaboration system, and the competence and training level of the SC-operators.

1. Introduction

The International Maritime Organization (IMO) defines a Maritime Autonomous Surface Ship (MASS) as a ship which, in varying degree, can operate independently of human interaction [14]. In order to develop and operate a MASS a radical and complete task and function re-allocation from manned execution to automated execution (mechanized and computerized) is necessary.

For those who regard ‘autonomy’ as ‘perfect automation’, the sheer discussion on ‘human interaction in varying degree’ in itself is regarded as ‘void’, since ‘perfect automation’ can do without any human control. Furthermore, in this line of reasoning these systems cease to exist as autonomous systems in case they need ‘outside’ help.

The above expressed either-or view on autonomy is both wrong and incomplete. It’s wrong because the autonomy concept incorporates more than ‘perfect automation’. It’s incomplete because it neglects the notion that autonomous ships are part of a wider maritime context, consisting of other vessels (autonomous and conventionally manned), vessel traffic service stations, harbour pilots, tugboats, and area specific regulations for example, in which collaboration cannot be avoided. Because of the shared nautical space, a MASS needs the ability to understand (the roles of) the other actors in order to be able to interact and coordinate. Hence, the ability to interact and ask for support based on some kind of world model is an intrinsic quality of autonomous systems and not a disqualifier.
1.1. The structure of the paper
The above shows that different conceptualizations about the meaning of ‘autonomy’ lead to different ideas in regard to the level of human involvement. Therefore, section two will provide a brief discussion on the concept of autonomy.

Furthermore, this paper takes the view that the performance of an autonomous ship depends on the quality and intelligence of the onboard technical control systems (henceforth the artificial navigator), the complexity of the maritime environment, and the human support that is made possible by means of a human-autonomy collaborative system. For the design of such an overall (socio-technical) system it means that at some level interaction between autonomous systems and human actors need to be taken into consideration. The outline and general specification of such an overall system design is described in section three. Section four discusses the Shore Control Centre (SCC) design principles that, from a human factors point of view, need to be in place in order to enable Shore Control operators (SCC-operators) to exercise meaningful human control. Section five will discuss the resilience of a human-autonomy collaborative system as the ability to deal with a range of expected and unexpected maritime conditions. Section six will provide the conclusions of this paper.

2. On autonomy and levels of automation
The concept of ‘autonomy’ and the concept of ‘automation’ have been used interchangeably in the literature, e.g. [5][17]. Differences in perception and interpretation of these concepts can create different expectations and principles for the collaborative design between system and humans. Therefore, it is important to have a clear understanding and definition of both concepts and the relation between them.

2.1. Defining autonomy
Despite the fact that automation and autonomy are related in terms of the performance of a ship, they are not equivalent constructs. Automation is physical technology (mechanized or computerized) viable for application in a defined environment. Autonomy is a state of situation awareness [9]. For a ship this implies robustness to the environment, independence in action or function, and self-determination of goals and allocation of its resources. Or to put it another way, autonomy can be a desirable design goal for automated systems [18] and hence for a MASS. In line with [18], this paper considers autonomy as a multi-faceted construct. In particular the following two system facets will be discussed:

- self-sufficiency or ‘viability’ in a given environment,
- self-directedness or capacity to function and to perform independently from other agents,

These facets are complex. For instance, self-governance is not just the absence of external control, it requires specific cognitive capabilities to learn but also to reason on a strategic level. Also, self-directedness does not mean that self-sufficient ships are independent in action since they will be part of a wider maritime context including among other things legislation, other vessels, pilot assistance, and vessel traffic service stations [3].

2.2. Contextual dependence
Self-sufficiency is related to the range of conditions the system can deal with and self-directedness refers to the range of conditions the system is given authority to conduct autonomously. Figure 1 depicts four ‘autonomy states’ based on four possible dimension ratios. Any imbalance should be avoided in system design for different reasons. For instance, when self-sufficiency is higher than self-directedness (bottom right), the system is not used optimally. If it is the other way around (top left), the system is allowed to handle situations that it is not capable of. This kind of overreliance is a dangerous condition and that should be avoided for all critical systems because it could lead to undesired states or even dangerous situations. Effective autonomy is possible when both dimensions are in balance (top right). As self-sufficiency is increasing with more advanced intelligent software, choosing the appropriate level(s) of self-directedness is an important task. Higher levels of self-sufficiency enable higher levels
of self-directedness. With increasingly more intelligent software available, the curve should be followed for optimal human-automation system performance.

![Figure 1. Autonomy consists of two dimensions. The curve shows the trajectory to follow when a gradual approach is chosen (based on [5]).](image)

Because the level of self-directedness and self-sufficiency may vary within different contexts, it means that with a constant (high) level of automation the self-sufficiency of an autonomous ship could be sufficiently high or ‘viable’ in environment ‘A’ but sub-optimal or less ‘viable’ in environment ‘B’. Therefore, self-sufficiency and self-directedness cannot be regarded as absolute or given system aspects but instead they depend on the operational complexity the autonomous system is in. Because of the large variation in operational complexity and in environment dynamics [25] a large variation of autonomy states is possible, which in turn require a varying degree of human support and/or support from other autonomous systems. From this it follows that autonomy as a system characteristic cannot be defined in absolute terms, and that the level of autonomy depends on the combination of the level of intelligence of the onboard software and contextual complexity.

3. The challenges regarding the human factor
In dealing with the challenges regarding the human factor, three different stages are distinguished within human-automation collaboration:

1. Supervision stage: The self-direction of the automation is low. The human operator supervises the system(s) 100% of his time and is not involved in other tasks. This strongly relates to Sheridan’s model of supervision [27][28].

2. Partial supervision/autonomy stage: The self-directness of the automation is higher. The human operator spends part of his or her time conducting secondary tasks. In case a complex or critical situation emerges that needs attention, the operator switches back to the primary task.

3. Intervener/full autonomy stage: Both self-sufficiency and self-directedness are high. The system is working autonomously 99.99% of the time. The operator is working on other tasks or on other systems. But even fully autonomous systems sometimes fail, and in these exceptional cases the operator does have to intervene or even take over control.

The supervision stage has been well-studied and is already common practice in many work environments. Therefore, this section will only look at the directions for solutions for the latter two less studied and less well-known stages.
The main challenge for partial supervision/autonomy stage, is to keep the operator aware of the status of the critical task and to enable him or her to resume control effectively when required. Both the human operator and the automation develop situation awareness (SA) relevant for the primary task [29]. Automation and human operators will continuously update their situation awareness. Both the union and the symmetric difference of their respective SA models are of importance [2], both for the detection of early signals as well as the need to adjust the human-automation collaboration agreements.

Ways to support human-automation collaboration within partial supervision/autonomy stage are:

1. Support upkeep of operator SA using supervisory displays [30]. This will help the operator decide whether his or her involvement at the primary task is required.
2. Provide SA recovery support after returning to the main task, for example using change detection support [35]. This enables better and faster switching to the primary task.
3. Increase reaction time by detecting early signals and providing on-time alerts for the primary task.
4. Just in time awareness: provide change detection and option awareness support for quick decision making when a critical event has occurred during the primary task.

At the intervener/full autonomy stage, active involvement of the operator is very rare. Therefore, it is not feasible or cost-effective to maintain a minimal level of SA of the primary task. Incidents are just too rare to warrant this effort. Also, regular SA recovery is not required as the operator would not conduct this task anymore under regular circumstances. In this configuration only the last two types of support for the partial supervision stage are relevant. The skill levels of the operator will be much lower than under partial supervision, as he or she hardly controls the system anymore (maybe solely during incident training in simulators). Hence automation support remains essential for safe and effective task completion, even in the intervening mode. This results in partly different types of support:

1. Increase reaction time by detecting early signals and providing on-time alerts for the primary task.
2. Just in time awareness: provide recognition primed decision-making, change detection and option awareness support for quick decision making when a critical event has occurred at the primary task.
3. Support operator with lack of skills: prevent the need for fully manual control but deliver lower levels of automation support.

Based on the review of the literature and solution concepts, designing human-automation collaboration at high system autonomy levels should meet the following principles of design:

• All systems, even “fully-autonomous” systems, should be considered from a joint human-automation collaboration viewpoint, because there will be always instances when human action in some form is required. Co-active design [17], focusing on observability, predictability and directability of all actors involved, has been proposed as a sound method to design this collaboration.
• Both human operators and automation need to develop an understanding of the situation, especially at the supervision and partial autonomy stages. This is in line with the distributed SA paradigm that holds the view that SA is not solely ‘in the mind’ or ‘in the world’ but is build up ‘in interaction’.
• Man, as intervener does not imply that the operator takes over manual control when automation fails. Because, when automation fails, it does not mean that it stops working on all levels. Human

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1 The recognition primed decision-making model is based on the assertion that operators can use their experience to generate a plausible option as the first one they consider.
support can be delivered, for instance, by making decisions in case automation fails to do so. But the execution of actions can be allocated to the automation. Because of the lack of skill of operators in complex future human-automation configurations, this kind of adaptive shift in collaboration agreements and authority provides a more promising approach.

From the above discussed human-automation collaboration principles, it follows that meaningful human control entails more than simply mimicking the bridge layout and conning station in an SCC. Especially SA recovery support and the detection of early signals requires a dedicated operator support tool. At TNO, an Intelligent Operator Support System (IOSS) has been developed (TRL-5) in order to demonstrate the above described design principles in support of dynamic positioning (DP) operators [33].

4. Concepts of Shore Control Centre design

In this section we will discuss how the human-automation collaboration principles described above can be applied within a future Shore Control Centre (SCC). A distinction will be made between a Shore Control Centre, being a kind of back office that provides logistical and technical support, and an SC-operator, being the person responsible for nautical support, and a Shore Control Station (SCS) that functions as the individual physical workstation which presents the necessary information and which enables the operator to exercise control.

The primary task of an SC-operator can be divided into two aspects. One is to build up SA of the nautical aspects, i.e. the operational picture of the marine area in which the MASS is sailing. The other aspect is that the SC-operator needs to be able to establish whether or not the self-sufficiency is high enough to deal with the situation and in which self-directedness is appropriate and safe. This not only requires an assessment of critical information on the basis of which the artificial navigator bases its decisions, it also requires an assessment whether the ship manoeuvres as it may be expected.

For this reason, the design concept of an SCS must facilitate the presentation of information regarding SA, the decision-making process and remote control for the operator. Also, the SC-operator must be able to communicate with conventional ships that sail in the vicinity of a targeted MASS, but also with other actors within the global maritime system, such as Vessel Traffic Services (VTS), port authorities and perhaps also with pilots and tugboats by using existing communication technologies [4].

4.1. Balancing the SC-operator workload

The general expectation is, that a future SC-operator will have to supervise several MASS-s, of the same or different type. The question concerning the span of control of an individual SC-operator, i.e. the number of individual ships a SC-operator is able to supervise, cannot be expressed in absolute numbers. The span of control highly depends on the level of self-sufficiency and self-directiveness of the ships under supervision and how these levels are distributed over the ships that constitute the case load of the operator. For instance, in case all ships under supervision cross the Atlantic Ocean, their self-sufficiency and self-directiveness levels will be sufficiently high and, as a consequence, the SC-operator workload will be relatively low (and with that, the span of control, i.e. the number of ships under control, could be enlarged). Whereas, if one of the ships under supervision enters a narrow fairway or a busy harbour, the self-sufficiency and self-directiveness levels will (relatively) drop, resulting in higher workload and higher vigilance levels. As a consequence, the span of control of the SC-operator will drop and may even, de facto, drop to even one ship.

The fact that different voyage stages have a particular timeline and can be estimated in advance provides the SC-operator the opportunity to anticipate to these higher workload situations. In [26], the

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2 An important aspect of SC-operator support is the question which and how much information can be transmitted to a SCC in order to adequately support the SA maintenance capability of the SC-operator. However, these technical and bandwidth issues together with latency issues are out of scope of this human factors related paper.
authors discriminate five voyage stages: leaving berth, departure from port, sea passage, and a stage in which exceptional circumstances occur. For each stage the autonomy mode changes for which the workload demands can be planned in advance with exception of the stage in which exceptional circumstances occur.

In addition, communication with third parties (e.g. other ships, vessel traffic service stations etc.) will increase the SC-operator workload significantly. From research on naval frigates it is known that communication, both external and internal, is difficult to combine with a primary task [34][31]. Altogether, it means that workload fluctuations can be predicted to some level but not always. The way forward to mitigate work overload is to apply voyage stage planning as described above, and to establish an adaptive workload balancing approach among several SC-operators to deal with workload fluctuations in a dynamic way [24]. For instance, when the cognitive resources for attention and workload are demanded by a single ship, the other ships that fall within the responsibility of the heavily occupied operator should be transferred to another SC-operator, within the own SCC, or within another SCC that functions as back-up centre. Also, when ships are crossing time zones, it is conceivable, and perhaps even necessary, to convey the supervisory responsibility from one SCC, e.g. in Europe, to another SCC, e.g. in the USA.

4.2. Situation Awareness recovery

The consequence of supervising multiple ships is that the SC-operator must switch between different ships and contexts, which comes with so-called (cognitive) task switching costs [23], being the mental effort and time it takes to reconstruct the situation awareness of the ship state and nautical context to which the attention shifts. However, the key question concerning shift of attention is: how does an operator know or determine which ship under supervision needs attention and which ship doesn’t? Is it for instance expected that the operator checks all the critical data from each ship on a regular basis? As argued above, it is not feasible to maintain a minimal level of SA of all the ships under control by cascading constantly from one ship to another. Instead, it requires a mechanism, i.e. a support mechanism, that helps the SC-operator to focus his or her attention.

The following mechanism is based on expected and pre-defined state changes:

- Divide a ship voyage into voyage stages of which levels of self-sufficiency are established or pre-set based on experience.
- This trigger mechanism should be accompanied by a process of SA-recovery, i.e. the build-up of the nautical picture including a risk assessment and the decision to intervene or not.

Additionally, a mechanism is needed to trigger the attention of the SC-operator in case of an unexpected critical situation. The trigger mechanism could be:

- The detection of early signals, i.e. anomalies in ship behaviour.
- The MASS itself triggering the attention of the operator based on a self-awareness capability. For instance, based on feedback that a sensor does not work optimally.
- This trigger class should also be accompanied by a process of SA-recovery, i.e. the build-up of the nautical picture including a risk assessment and to decide on the appropriate intervention.

Because it is envisioned that a single SC-operator has to monitor and has to control several MASSs, intelligent support of operators should be part of human-automation collaboration design to meet the cognitively demanding task of switching between different ships and contexts. The IOSS [33], introduced above, is developed to support operators in such a way that maintaining a continuous level of SA of autonomous systems is no longer needed because the task of monitoring a ship is handed over to the IOSS. This makes it possible for an SC-operator to pay attention to another ship or to execute a secondary task. When the situation of a ship changes in such a way that the involvement of the SC-operator might be required, the IOSS will trigger the attention of the SC-operator. The critical conditions
under which it is necessary to bring the SC-operator back into the loop can be pre-defined by the SC-operator as so-called cooperation rules. Furthermore, in dealing with a possible critical situation, the SA recovery of the SC-operator is supported by offering context specific information instead of a situation in which the SC-operator self must search for information by means of an interface.

4.3. SC-operator competence and skill enhancement

Currently, not much research has been done into the required competences and skills of the SC-operator of the future. To some extent they are regulated by the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [16]. Additionally, the IMO is currently carrying out a scoping exercise assessing IMO-instruments, including reviewing STCW regulations, to see how they may apply to ships with varying degrees of autonomy [15]. The interim guidelines for trials with autonomous ships stipulate that “onboard or remote operators of MASS should be appropriately qualified for operating MASS subject to the trial (2.3.2, p.2)” . The guidelines further state: “For the safe, secure and environmentally sound conduct of MASS trials, the human element should be appropriately addressed. The trial should consider the human-system interface as harmonization between human centred design and automation is a key component of MASS (2.4, p.2)” . Other organisations, such as DNV-GL [8], Bureau Veritas [6], and the UK Maritime Autonomous Systems Regulatory Working Group [21], published guidelines with equivalent qualifications and requirements as mentioned in STCW. The Institute of Marine Engineering, Science 

& Technology evaluated future skills requirements by a series of surveys and of roundtable discussions. The final conclusion of the report [10] is that “for the foreseeable future, autonomous systems will remain unable to make critical decisions based on sound judgement. So, the challenge lies not in teaching humans to trust machines, but in providing them the skills and competencies to know when to stop trusting and overrule them (p. 23)”. However, the report fails to address the required skills and competencies.

In order to gain understanding of the additional competencies of the remote operator, simulator experiments were conducted on the ship bridge simulator at the nautical school in Rotterdam, using the instructor station as a Shore Control Centre. Twenty nautical students, nearly graduated, performed the task as an SCC operator of three autonomous vessels with same manoeuvring characteristics, sailing in three different coastal areas with navigational obstructions, vessel traffic zones, medium traffic (about four vessels in each area) and good visibility. The experimental design was, that due to a failure of the autonomous systems the operator had to control the autopilot, rudder and thruster of the three autonomous vessels. The scenarios with a runtime of about 30 minutes contained traffic situations where the operator had to perform manoeuvres to avoid collision according to the COLREGS, taking into consideration navigational obstructions. All other vessels in the scenario were visible on radar and AIS information was received.

Despite the relative low complexity of the task (not all watchkeeping tasks were performed, e.g. plotting the position of the vessel in the ECDIS, VHF communication with shore stations and all vessels complied with the COLREGS), from observations and briefings it became clear that the cognitive workload was high during the control of the three vessels. The central problem was to regain situation awareness when switching between the autonomous vessels, especially when there is a close quarter situation and the operator has to focus for a longer time than planned. This is in line with [36], who report the ‘Constant reorientation to new tasks (p. 1042)’ in the context of remote container handling. Due to the high cognitive workload, information from AIS was most times not cross checked with radar information. These findings support the above described necessity of workload balancing mechanisms for SC-operators.

A MASS will have similar manoeuvrability characteristics and must apply to the COLREGS as any other conventional manned sea going ship. Therefore, it is necessary for the SC-operator to master the STCW-skills and competencies (both knowledge and practice). However, remote navigation and supervisory control possess additional challenges compared to a navigator who is located at the bridge because the behaviour of a ship and the environmental circumstances (wind, waves, currents) can only
be assessed in an indirect way by means of a two dimensional display, instead of being immersed and tangibly connected with the ship and the elements. This requires additional competencies:

- The ability to built-up situation awareness of the nautical situation, e.g. vessel traffic, distance, speed and circumstances, e.g. wind, waves, currents from a 2D-interface.
- The ability to translate required manoeuvring changes, e.g. speed and course, in adequate high-level instructions for a MASS.
- The ability to deal with different ship types and conditions that result in a large range of manoeuvring characteristics. Normally, it takes time to learn how particular ships behave under different conditions.
- Thorough knowledge, including the limitations of various autonomous control systems, including Advanced Sensor Modules, Remote Manoeuvring Systems, and Deep-Sea Navigation Systems.
- Resource Management, Teamwork and Leadership in order to improve safety [16]. These so-called non-technical skills, i.e. human factors training or soft skill training, are not new in the maritime industry, but were recommended for ship operating companies, and training was therefore carried out on a voluntary basis. In line with the renewed emphasis on non-technical skills for onboard bridge teams, this should also apply for SC-operators. Because not only will SC-operators be responsible for the external communication with third parties (ships, VTS-stations etc.), it is also very likely that a SC-operator will be part of a SCC-team.

In section 4 it is stated, that in the intervener/full autonomy stage the skill levels of the operator will be much lower, in comparison with the partial supervision/autonomy stage, as he or she hardly controls the system anymore. Is this contradictory with the above claim that SC-operators should have and maintain STCW-skills and additional competencies? No, it’s not, because it is stated that the nautical skill level will be much lower, but that does not mean that it may be entirely absent. The question, which competencies will be essential in the long term and which less in this context, must be determined by future human factors research. In the far future however, it can be expected that the SC-operator’s competences will likely shift from skill level (hands-on experience) to domain knowledge level and general nautical competences. In the short run, SC-operators still need the ability to shift between the intervener/full autonomy stage, partial supervision/autonomy stage and even supervision stage operations when circumstances dictate, operations in which STCW-skills are still relevant.

5. The resilience of a human-autonomy collaboration systems
The sailing of a vessel always takes place in a dynamic environment due to different weather and hydrodynamic conditions, and traffic. In a dynamic environment it is important for a system to have the ability to observe, anticipate, and respond, i.e. to be resilient. In the definition of Eric Hollnagel [12] a system is resilient if it can adjust its operation before, during or after events (changes, disruptions and opportunities), and thereby maintain the required operations under both expected and unexpected circumstances. In terms of the above, resilience is the ability of a system to deal with a range of conditions. In conventional shipping, resilience is a characteristic of a socio-technical system. It means that a ship system involves a combination of people (socio) - such as individuals, teams and organizations - and technical elements - such as automated systems, computers and instruments – that interact and collaborate to support organizational activities. The basic assumption of the resilience approach is, that accidents occur when the resilience (ability) of a system falls short in dealing with certain conditions. Hence, resilience engineering is focused on extending the resilience ability of socio-technical systems.

Shipping is perhaps the most international of all the world's great industries - and one of the most dangerous [15]. Worldwide, almost every week there are accidents with commercial ships [7]. According to the IMO and various insurance companies, seventy-five to eighty per cent of the number of accidents is caused by the human factor [1]. The claim that autonomous shipping will be safer than
conventional shipping, which now can be rephrased as the claim that autonomous shipping will be more resilient than conventional shipping, is based on the assumption that when human crews are replaced by technology the accident rate will be reduced with eighty per cent. Firstly, this assumption is fuelled by the fact that the label 'human error' is always interpreted differently and has become a collective term for every involvement of 'humans' in situations where 'things are going wrong' [12] Also, to conclude that if eight out of ten accidents are partly due to humans, that therefore sailing without a crew will be safer is not valid. Statistically speaking, only one out of ten thousand events turns into a failure [13]. From the ninety-nine thousand nine hundred ninety-nine non failures we do not know in how many cases crews were resilient enough to turn a near-disaster into a safe situation, that otherwise would have been a disaster. And we certainly do not know whether autonomous ships can produce the same level of resilience. Secondly, it’s not correct to state that autonomous shipping takes the human ‘out-of-the-loop’. Yes, the bridge crew is taken off the ship, but (partially) replaced by SC-operators as part of a human-autonomy collaboration system [21]. Therefore, the safety claim, often presented as rationale for autonomous sailing, should be rephrased into the question whether the resilience of human-autonomy collaboration systems will be equivalent or better than conventional manned socio-technical ship systems.

According to Hollnagel [11], resilience is based on four essential abilities: monitoring, responding, learning and anticipating. The starting point is that a system can be made more resilient by reinforcing these four essential abilities. These abilities differ hugely between humans and artificial systems, both in terms of internal mechanisms, and in range and richness of their world models. This will be illustrated with an example.

A Dutch start-up, called Captain AI, recently sailed autonomously in the port of Rotterdam. The artificial navigator was trained through virtual simulation to recognize elements in the environment and to react as learned. Because SA starts with perception of the elements in the environment, the actual sensor suite that is implemented will have de facto a selective world view and the autonomous vessel will have a selective and limited SA in combination with the learning algorithm. This has consequences for adaptability. To understand this, the distinction between ‘work as imagined’ (WAI) and ‘work as done’ (WAD) is introduced [11]. WAI is the ‘outside-in’ view of the blunt-end of the organization. WAD is about the resources which are actually needed to execute operations at the sharp end of the organization. The danger of designing systems from a limited WAI-point of view, is that the resources, systems and mechanisms are too rigid to adapt to unexpected (from the perspective of WAI) circumstances. For the Captain AI example, it means that the system is not able to react to a set of circumstances that falls outside the scope of what is perceived and what is learned. Also, what the Captain AI algorithm has learned within a geographical specific area cannot be generalized to other distinct areas.

This domain or task specific intelligence is known as weak AI, which, in contrast to strong AI, cannot be generalized to other domains and tasks. This, in contrast to the general intelligence qualities of humans, i.e. the extent to which a type of cognitive skill (e.g. learning a foreign language) is associated with other cognitive skills (e.g. mathematical skills). Paired with the general ability to deal with fussy (ill-defined) situations, to be creative, and to improvise results in high resilience ability. Of course, artificial intelligent systems also have advantages compared to humans. They do not get tired, do not have vigilance problems and can analyse huge amounts of data necessary for applications as face recognition, diagnostic systems etc. Because this form of human-computer dichotomy is considered counterproductive, Licklider [20] argued for the concept of human-computer symbiosis as early as 1960. With the introduction of the human-autonomy cooperation system, this paper endorses this line of reasoning.

Woods [37], calls the limited flexibility of system ‘brittleness’, i.e. a sudden collapse or failure when events push the system up to and beyond its boundaries for handling changing disturbances and variations. As the opposite of brittleness, it is important that a system has ‘graceful extensibility’, i.e. the ability of a system to extend its capacity to adapt when surprise events challenge its boundaries. A way to avoid brittleness as much as possible is to select or create a less complex and well controlled
area of operations to accommodate a MASS as much as possible. An example of which is the Yara Birkeland the first ever zero emission, autonomous ship [19]. The goal of this challenging project is not only to build a newly designed ships but also to build dedicated terminals and infrastructure (e.g. charging the ship’s batteries) to fully accommodate the Yara Birkeland operation\(^3\). Also, the ship will be tested in the Brevik area of Southern Norway, which provides an ideal marine area to experiment with MASS operations because the Yara Birkeland will sail on two fixed and pre-defined routes. In addition, the Brevik area has VTS which will be used for traffic monitoring and for nautical support. Also, the Yara Birkeland will be monitored and facilitated by two additional SCC-s, one for the logistic processes and one for technical and maintenance assistance [32].

The expected brittleness and rigidity of artificial systems will lead to reduced resilience in dealing with fussy and less well-defined situations, i.e. in terms of the above, could lead to reduced levels of self-sufficiency in unexpected and difficult situations. This means that a SC-operator, being part of the human-autonomy collaboration system, will mostly be involved in critical and difficult situations, that the artificial navigator cannot handle for whatever reason. The frequency with which exceptional situations occur is expected to be low, resulting in low experience and training opportunities for SC-operators. This adds to the challenge of timely turning critical situations into safe situations.

Currently, not much is known of the resilience ability of the human-autonomy collaboration systems for safe navigation, particularly in realistically complex situations. Hence, at this stage of MASS development it is not possible to prove that autonomous shipping can establish safety levels equivalent to conventional shipping, let alone prove that autonomous shipping is or will be more resilient than conventional shipping.

6. Conclusions
This paper has provided an overview of the aspects related to meaningful human control in autonomous shipping. Autonomy is described as a multi-faceted construct including self-sufficiency and self-directedness which are related to a range of conditions a ship can deal with. This means that autonomy levels will vary in different operational situations. From this it follows that autonomy as a system characteristic cannot be defined in absolute terms and that the level of autonomy depends on the combination of the level of intelligence of the onboard software and contextual complexity. As a consequence, active operator involvement and workload will fluctuate and will sometimes be unpredictable. In case of supervising multiple ships, it is not feasible to maintain a minimal level of situation awareness of all the ships. In order to facilitate operator situation awareness recovery, task switching support, and workload balancing it takes more than mimicking the bridge layout and conning station. An Intelligent Operator Support System concept is outlined as alternative for implementing the human-automation collaboration principles.

Whether the large-scale application of MASS-s will provide equivalent safety and resilience levels compared to conventional manned ships will largely depend on the intelligence of the onboard control systems, the design quality of the human-autonomy collaboration system, and the competence and training level of the SC-operators.

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\(^3\) Due to the Covid-19 pandemic and the changed global outlook, Yara has decided to pause further development of the vessel and will assess next steps together with its partners [19].
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