

# Characterization of autonomy in merchant ships

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**Abstract**—Autonomous ships are creating significant interest in the maritime world and the need for a more consistent definition framework is very apparent. This paper suggests building a framework based on the SAE J3016 standard for autonomous cars, but to extend it where necessary. One main difference is that ships are larger, slower and fewer than cars, but that consequences of accidents may be more severe. This is a typical characteristic of industrial autonomous systems. For ships one also must consider a more complex functional system (duration of voyage, energy, steering, hull integrity and stability etc.) as well as a very likely possibility that autonomous ships will be supervised from shore. This points to a constrained autonomy, where the system has programmable limits to the actions it may take. This creates a more complex taxonomy, in terms of the operational scenario possibilities, in how the control problem is solved and how responsibilities are divided between humans and computer systems.

**Keywords** — *Autonomous systems, levels of autonomy, autonomous ships, industrial autonomous systems, constrained autonomy.*

## I. INTRODUCTION

Internationally, there is an increasing interest in autonomous and unmanned ships. MASS (Maritime Autonomous Surface Ships) has been suggested in the International Maritime Organization (IMO) as a general name for these new ship types. However, there is still much confusion about what exactly autonomous means in the context of merchant ship. Is a dynamic positioning system autonomous or only automatic? What is the difference between automatic and autonomous? Is a remotely controlled ship autonomous? Unmanned is also an ambiguous concept: The ship can have a periodically unmanned bridge, but with crew available on board to take over in case of trouble, or there can be an operator in a shore control centre that is always ready to intervene or even remotely control the ship. An improved classification scheme is needed to distinguish between these and other operational variants.

In [1], the concept of industrial autonomous systems is introduced to distinguish industrial autonomous systems from, e.g. military, scientific exploration or research oriented autonomous systems. The term is used to describe autonomous systems that are used cost-effectively in commercial operations, which have a high value as an asset and have a high potential for causing damage if used improperly. Autonomous merchant ships obviously satisfy these criteria. Industrial autonomous systems are challenging because they must be a trade-off between cost-effective solutions, high safety and high

availability requirements. Autonomous merchant ships are particularly challenging, as they also need to be extremely efficient at what conventional ships do best: Transport large volumes of cargo over long distances at minimal cost.

The very high cost-effectiveness of today's shipping will also cause autonomous ships to look very different from conventional ships. In short, an unmanned ship is not a conventional ship without a crew, it is a completely new component in an integrated transport system [2].

Conventional ships are the subjects of extensive regulation both at the national and international level, but current legislation has no support for ships that can operate independent of human control. Thus, as the interest in unmanned and autonomous ships grows, the problem of a regulatory framework for autonomous ships is becoming increasingly acute. In June 2017, the Maritime Safety Committee (MSC) of IMO decided to start an investigation into what changes are required in its regulatory system to include these types of vessel in the international legislative framework. A critical part of this work is again the characterization of the autonomous ship, as this will be a necessary basis for defining appropriate requirements to the diverse types of automated ships and their onboard or on shore systems. The characterization needs to be multi-dimensional as it will have to describe automation level, manning levels on the ships and the eventual support functions and crew on land.

This paper will extend current autonomy definitions and develop a more holistic characterization system for autonomous ships. This will be done by identifying the dimensions that need to be covered and, furthermore, suggest a set of classification values for each dimension. This includes, e.g. the autonomy level, the presence of qualified crew or persons on the ship as well as the capabilities of a dedicated shore control centre (SCC).

The work presented here is the latest result of an iterative process that started in 2012 with the MUNIN project [3]. It has continued through various other activities and projects and is probably still not finished.

## II. SOME DEFINITIONS

### A. *Autonomy*

According to Webster's online dictionary [4], autonomous, when related to a vehicle, can be defined as "navigated and maneuvered by a computer without a need for human control or intervention under a range of driving situations and

conditions". This is a useful definition, but it does not provide any unambiguous way to qualify autonomous, e.g. into partially or full. The "degree of autonomy" will be dependent on several factors (here in the context of merchant ships), e.g.:

- How complex is the operation? What other ships are there and how much space has the ship for manoeuvres? What degree of environmental variability, e.g. in obstacles or weather is present?
- Is there a person on the bridge or in the engine room supervising the ship? Is there a person on board that (after a short delay) can take control in cases where the autonomous control system reaches its capability limits?
- Is there someone on shore (continuously) supervising the ship and which, after a short delay, can intervene in demanding situations?
- Where humans and computers cooperate, how is the work divided between the two? What are the criteria for when a human is required to take over control?

This ambiguity is not special to ships. In the following, we will use a modified version of Webster's definition: "Autonomous, when related to a ship, is defined as navigated and maneuvered by a computer with no or limited need for human control or intervention under a defined range of situations and conditions".

#### B. Automation

When the above definition of autonomy is considered, e.g. for a track pilot or a dynamic positioning system, it is no doubt that these functions also can be said to be autonomous, although many people would argue that they are merely automatic. In our experience, it is not generally useful to distinguish too sharply between automation and autonomy. Automation and autonomy are regions in a continuum where it is difficult to set up specific criteria for a function being the one or the other. We will come back to this later, when discussing degrees of autonomy.

In the following, we will use the term "automation" to refer to computer based decision and control programs. The concept of autonomy is considered the emergent behaviour of the system while automation is the functions implemented in the computers to realize autonomy.

#### C. Unmanned

Unmanned is also an ambiguous term in the context of autonomous ships. The first problem is what functions one refers to: The navigation bridge, the engine control room, other control positions or the whole ship.

Even when this has been decided, there are at least three different manning levels that can be defined [10]:

- *Continuously manned control*: People are always available at the control positions on the ship;
- *Periodically unmanned control*: Qualified personnel is available on the ship, but the control positions may be unmanned in periods, e.g. at night in calm weather and little traffic; and
- *Fully unmanned control*: No qualified personnel are available on the ship to operate the control positions. This may only be for parts of or the full voyage and there may still be other persons on the ship.

For all manning levels, one may apply as much or little autonomy as one needs. Thus, autonomous does not imply unmanned control or vice versa. In the following, we will use the above qualifications when discussing manning levels and in addition we will use the term "unmanned ship" for ships that have no persons on board at all.

#### D. The Shore Control Centre (SCC)

The MUNIN project performed a first investigation of the possibilities inherent in unmanned and autonomous ships [3]. One of the conclusions was that to make the concept cost-effective, a continuously manned shore control centre (SCC) will normally be required to oversee the operation of the unmanned ship and to assist in complex situations [5]. This creates even more possibilities for combining manning and autonomy, by considering manning both on the ship and in the SCC. The SCC can in principle be operated in two main modes:

- *Supervisory control (SC)*: The SCC operator monitors a number of ships and is not directly performing control actions. The operator will change operational parameters, e.g. speed or track, when necessary, but this will be part of normal procedures.
- *Remote control (RC)*: The SCC operator controls the ship by giving various levels of commands directly to the ship. This is used in situations when the automation systems are not fully able to cope with the situation by themselves or when the ship has only limited autonomy and requires human assistance in most operations.

#### E. SAE autonomy levels

Table I lists the autonomy levels defined in SAE J3016 [11] and a brief description of what they mean. The term "Other" in the "Fallback" column refers to a passenger in the car that takes control in case of problems. For ships this could correspond to backup crew on the ship or in the SCC. We will refer to the levels and the concepts later in the paper and explain how they can be applied in the maritime domain. We retain the basic principles, but with some major modifications.

TABLE I. AUTONOMY LEVELS ACCORDING TO SAE J3016 [11]

Autonomy level		The driving task		Fallback	Operational domain
AL	Description	Steering	Tactical		
0	No driving automation	<i>Driver</i>	<i>Driver</i>	<i>Driver</i>	<i>n/a</i>
1	Driver assistance	<i>Driver &amp; system</i>	<i>Driver</i>	<i>Driver</i>	<i>Limited</i>
2	Partial driving automation	<i>System</i>	<i>Driver</i>	<i>Driver</i>	<i>Limited</i>
3	Conditional Driving Automation	<i>System</i>	<i>System</i>	<i>Other</i>	<i>Limited</i>
4	High driving automation	<i>System</i>	<i>System</i>	<i>System</i>	<i>Limited</i>
5	Full driving automation	<i>System</i>	<i>System</i>	<i>System</i>	<i>Unlimited</i>

Note that the driving task has been divided into two: The simpler "steering" task and the more complicated "tactical" task, which is called the "object and event detection and response" (OEDR) tasks in the SAE standard. This distinction will also partly be used in our suggested levels of autonomy, as discussed in section IV.E.3.

### III. WHY CHARACTERIZE SHIP AUTONOMY?

#### A. What needs to be captured?

The "level of autonomy" needs to capture many factors that determine how independent the system is. The main factors are shown in Fig. 1 and are further discussed in section IV. This figure is specifically for a ship and it is obvious that the factors and their weight will be influenced by the type of system, e.g. a car, a flying drone or a terrain exploring robot. This may be one of the reasons why there are several different definitions of degrees of autonomy as discussed in the next section. Most schemes define a one-dimensional "level of autonomy" that captures only a part of the general characterization, but typically the part that is relevant for the system at hand.

#### B. Existing taxonomies

In [6], twelve different definitions of "level of autonomy" are examined and even more have become available, as autonomy has started to extend to ships, see e.g. [7], [8] and [9]. None of the references adequately addresses all the factors illustrated in Fig. 1. and it has been necessary to start looking for other forms of definitions. One attempt at a more extensive definition has been published by the Norwegian Forum for Autonomous Ships (NFAS) [10]. This is the basis for the work described in this paper. Both our definitions are strongly influenced by the SAE J3016 standard [11].

#### C. The purpose of the taxonomy

A main goal in our work has been to provide a consistent definition of ship autonomy that makes discussions about autonomy in ships less ambiguous. Furthermore, it has been important to develop definitions that can capture all important aspects of ship autonomy, including ship and SCC manning level.

Another issue which is becoming more relevant is the development of international technical standards. As an example, industry developed test standards will require a more formal definition of the attributes and characteristics that are to be tested. This will also apply, e.g. to Hazard Identification and

related risk assessment methods where good definitions can aid in providing more complete analysis coverage [12].

Overarching the standardization work, the ongoing work in IMO and in national administration to develop acceptance criteria for autonomous ships will also require better definitions of autonomy levels and functionalities. Different levels of autonomy will most likely require different levels of rigor in testing and test methods.

Levels of automation or autonomy has also been used as basis for discussing human-automation design of complex systems and, in particular how humans interact with automation. This is a complicated issue [13], [14].

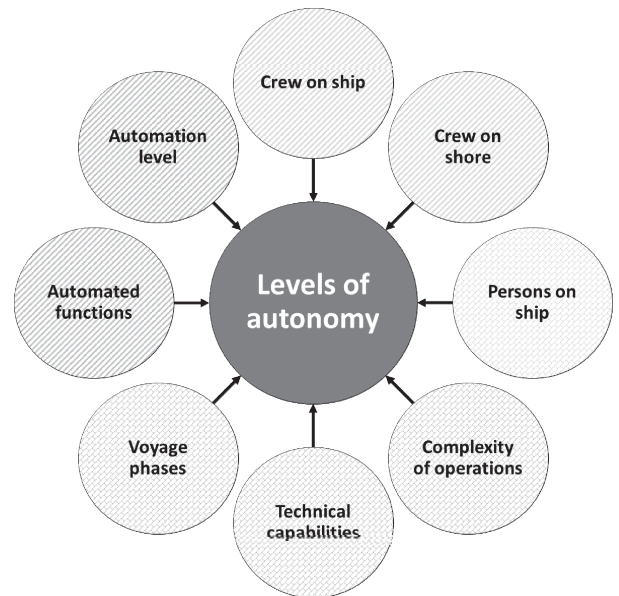


Fig. 1. Defining the level of ship autonomy

## IV. A PROPOSED TAXONOMY

### A. General principle

When examining Fig. 1., the different influencing factors can be divided into two groups:

- *Operational Design Domain (ODD)*: This captures the factors that influence the complexity that human operators and autonomous control functions must handle.



- *Dynamic Navigation task (DNT)*: This defines the functionalities in the autonomous system and manning levels that satisfy requirements derived from the ODD.

These two concepts are taken directly from the SAE standard for autonomous cars [11], but the term DNT has been renamed from Dynamic Driving Task (DDT) which was used in the car context. Taking the factors shown in Fig. 1., they can be grouped as illustrated in Fig. 2. The following sections will give some more details on these factors.

Dividing the characterization of autonomy into the problems that are to be solved (ODD) and how they are addressed (DNT) gives a more precise description of the autonomy the system exhibits. The DNT also allows us to distinctly describe tasks that are planned to be solved by humans and automation respectively.

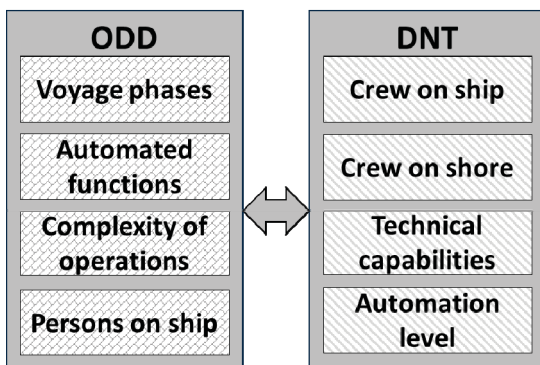


Fig. 2. Grouping autonomy attributes

### B. Operational Design Domain – ODD

Any autonomous system need be designed to satisfy the external requirements given by its intended operation. This is the vehicle's "Operational Design Domain" (ODD). For cars, which is the target of the SAE standard, this is mostly given: All relevant road conditions that a car normally encounters. For ships, this is much more complicated. The operational domains span from world-wide tramp shipping to short distance and sheltered water highway ferries. This means that the ODD must be defined for each operational case. This can contribute to a more systematic characterization of autonomy as we can provide a well define description of the ship's operational domain and requirements. The following paragraphs discuss each of the main components of the ship's ODD as presented in Fig. 2.

#### 1) Voyage phases

All ship voyages have distinctive phases with very different challenges for the automation system. In practical terms, this may mean that one will utilize a different division of work between automation and humans in the separate phases of the voyage. Fig. 3. shows some typical voyage phases.



Fig. 3. Voyage phases

In this example and with an unmanned ship, one would probably use remote control combined with automatic track and berthing control during the port approach and berthing phases. During sea passage, the ship could be close to fully autonomous, except in exceptional situations with very dense traffic or heavy weather where more operator support may be necessary.

#### 2) Automated functions

A merchant ship is often looked at as a "village on the seas". The ship must maintain many functions related to safe passage, energy production and life support for crew and passengers. A few of these functions are irrelevant for unmanned ships, but in general, the autonomous ship must automate more than the navigation related functions. In [10] a relatively detailed break-down of ship functions from 10 main groups are provided. One particularly challenging group is the technical, covering the problem of efficiently maintaining technical ship systems without crew on board.

#### 3) Complexity of operations

The area the ship is sailing in, time of day and year, availability of aids to navigation and detailed charts and the traffic density of other ships are obvious contributors to the complexity of operations. The complexity can be reduced, e.g. with dedicated sailing lanes, adjustments to legislation to provide special navigational status to autonomous ships or more extensive infrastructure support.

#### 4) Persons on ship

This issue is a major problem when one tries to develop an autonomous passenger ship. Passengers are very difficult, if not impossible, to put into a well-defined behavioural envelope. This means that automating functions related to passengers and passenger safety is very difficult. This applies to safety services during evacuation, avoiding that passenger enter prohibited areas or keeping track of passengers during boarding or disembarkation.

### C. Dynamic Navigation Task – DNT

In the SAE J3016 standard, the Dynamic Driving Task (DDT) defined the operations that the car's automation system would need to implement to handle the complexity of the ODD. For ships we suggest renaming this to the Dynamic Navigation Task (DNT) as illustrated in Fig. 4.

A difference from the SAE definition is that we have adjusted the DNT to also include the operations that the human operators are supposed to perform.

This means that the DNT is divided into two components:

- *The control system DNT (CS-DNT)*: The part of the DNT that is handled by automatic control functions. This is the medium shaded area.
- *The operator exclusive DNT (OE-DNT)*: This is the part of the DNT that the automation system is not designed to handle, but which is still part of the ODD. This is the black area of the DNT.

As will be discussed later, the relative sizes of these areas can then be used to define general levels of autonomy. We will

also introduce a shaded variant of the CS-DNT. This is used to illustrate "constrained autonomy".

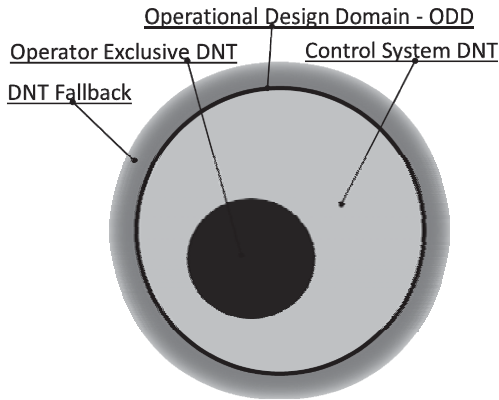


Fig. 4. DNT divided into operator and automation parts

#### D. DNT Fallback

In addition to the DNT or, rather the DDT, SAE also defines a fallback functionality. This represents functions that are activated in case the ODD is exceeded, typically by defects in sensor or communication systems. The fallback has sometimes been called a "fail to safe" mode, but it is in most cases impossible to guarantee that these backup procedures can take it to a fully safe state. SAE refers to this as a "minimal risk condition". The design of the DNT fallback will obviously be a critical part of the safety features for the autonomous ship. It need to be designed by doing extensive hazard identification and risk analysis on the ship and its operational characteristics.

The DNT fallback proposed in this paper is somewhat different from that proposed by SAE. As we include the operator's expected contribution in the DNT, the fallback will mainly cover situations where the operator is not able to intervene in a satisfactory way, e.g. as communication or other technical functions are lost or if adverse situations arises too fast for the backup crew to respond in time.

#### E. Composition of the DNT

This section discusses the main elements shown in the DNT in Fig. 2.

##### 1) Technical capabilities

Most ships have practical limitations in their manoeuvrability and the environmental states they can operate in. Autonomous ships may have additional limitations in sensor

and object detection systems. However, the capabilities of the ship must satisfy the overall requirements of the ODD. It is possible to adjust the ODD by, e.g. limiting the operational window to daytime only or define limits to winds or sea state the ship can operate in. In addition, it may be relevant to add new infrastructure on shore to further simplify the onboard systems. This may include additional positioning systems, automatic mooring systems, additional shore sensors and improved communication systems.

##### 2) Crew on ship or shore

An important part of the DNT concept is the division between the OE-DNT and the CS-DNT. This is one of the main determinants for the total complexity of the system. As concluded in [5], it is unlikely that an autonomous ship will sail without supervision from an SCC and this gives important possibilities to reduce overall complexity by assigning tasks that are difficult to automate to the SCC crew. This requires well defined mechanisms for alerting the SCC crew when they are needed. This is the background for defining the term "constrained autonomy", where the ship has programmable limits or constraints to the actions it can take, such as a maximum deviation from planned speed or track, before crew must be alerted to intervene.

The main disruptive force in autonomous shipping lies in the unmanned ship. This allows completely new ship designs and lower operational costs, particularly for smaller vessels [2]. However, creating an automation system that provides full autonomy in all situations is very challenging, if not impossible. Thus, the possibility of reducing this complexity by using a combination of automatic systems and a SCC is an attractive and often necessary proposal.

##### 3) DNT Autonomy level

The autonomy level represents only the relative split between the CS-DNT and OE-DNT and is not directly related to the complexity of the ODD. We have defined five basic types of autonomy as illustrated in Fig. 5.

The levels correspond well to the SAE autonomy levels (AL) listed in Table I.

##### a) Operator controlled (AL0-1)

The ship is always operated by the crew on the ship or in the SCC (remote controlled). Automation systems may provide decision support or limited automatic control, e.g. as in an auto pilot or track pilot. This is the situation on most ships today.

##### b) Automatic (AL2)

The ship systems can operate automatically for a very

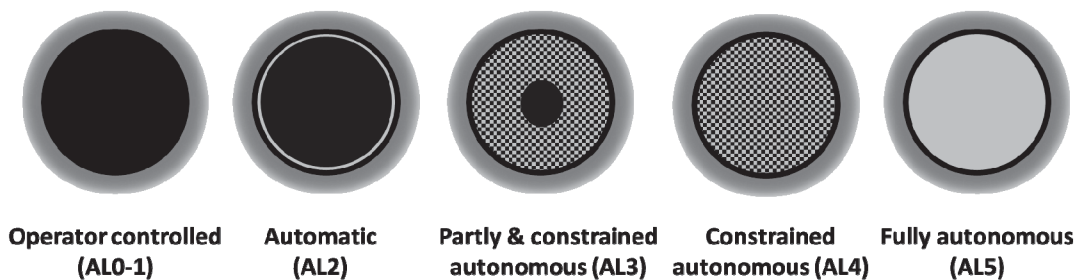


Fig. 5. Five basic types of autonomy

specific function, typically as a dynamic positioning system works today. An operator is required at all times to handle all deviations from expected operational domain, e.g. if an obstacle is seen in the operations area. This level is appropriate for automatic berthing or other situations where very accurate control is needed and where less deterministic and autonomous problem handling is unwanted. Fully automatic berthing and transit for a highway car ferry is a likely example of this. This is similar to the automation of the steering function in AL2.

*c) Partly and constrained autonomous (AL3)*

The ship can perform certain tasks in the DNT autonomously, e.g. transiting low traffic sea areas. The automation systems will be constrained by programmable limits to the actions it can take without human approval. If constraints are violated, an alert is given, typically to the SCC operator. This is the most likely automation level for the autonomous ship projects seen today.

*d) Constrained autonomous (AL4)*

The ship can operate autonomously within all the ODD, but it has the same constraints to its actions as mentioned in the previous paragraph, e.g. limits to speed and track deviations.

The focus on constraints to autonomy is linked to the analysis that led to the inclusion of a SCC for most autonomous ships [5] and the general determinism requirements implied by industrial autonomous systems. Constrained autonomy gives better determinism for system behaviour and avoids problems related to intentional attempts to influence course or speed of the ship, e.g. by hostile parties arranging false collision threats.

*e) Fully autonomous (AL5)*

The ship systems can perform all its DNT tasks without human intervention. There are no operational limits beyond those defined by the ODD. This mode is necessary for autonomous ships that operate without a SCC. For reasons mentioned previously, this is not a very likely mode, except for small crafts or for operation in highly controlled areas.

*F. Combining manning and autonomy levels*

There is obviously a dependency between the allowable crewing levels and automation levels. This is illustrated in Fig. 6. The figure shows the three different ship manning levels that are relevant (see sec. II.C) together with autonomy levels and three different SCC configurations: No SCC at all; an SCC that continuously monitors and controls the ship (Remote Control – RC); and supervisory control (SC) where operator only intervenes when alerted to do so. The latter is the type of SCC that was suggested by the MUNIN project [15], [5].

	Continuously manned			Periodically unmanned			Fully unmanned		
	No SCC	RC	SC	No SCC	RC	SC	No SCC	RC	SC
<b>Operator controlled</b>				XXXXX		XXXXX	XXXXX		XXXXX
<b>Automatic</b>				XXXXX		XXXXX	XXXXX		XXXXX
<b>Partly &amp; constrained autonomous</b>							XXXXX		
<b>Constrained autonomous</b>							XXXXX		
<b>Fully autonomous</b>									

Fig. 6. Crewing level and automation

The very light grey cells show possible, but unlikely combinations. This is due to "overkill" in combining too high autonomy levels with too intensive manning. The medium dark indicate some possible, but probably not optimal solutions, and the darkest cells the most likely configuration. Cells marked with 'X' represent impossible combinations. The latter is mainly because a backup crew is required in some of these case and response time requirements will limit what type of SCC one uses in the other cases. Note that this is indicative and that an actual combination needs to consider the required response times from the crew in case an alert is raised, and the general safety of the proposed solution.

V. SUMMARY AND CONCLUSIONS

Unmanned and autonomous ships have the potential to radically change maritime transport and act as a disruptive force in the business sector. However, they will not replace conventional ships, but will be introduced in new transport solutions, much more integrated in the logistics chains. This, and the facts that ships are high value assets with significant damage potential ("industrial autonomous systems") and that they need to be a cost-effective solution to the transport needs at hand, will limit the type of autonomy used. Most autonomous ships are expected to be operated in a partly and constrained autonomous mode with a permanently manned shore control centre as backup.

To provide a more systematic method for describing ship autonomy, we have proposed a taxonomic system, consisting of the following elements:

- The concept of a Shore Control Centre (SCC) to cover the likely situation when an autonomous ship is monitored or controlled from a remote position.
- A definition of general manning levels for ship and for SCC.
- The introduction of the concept of "constrained autonomy" to provide programmable limits to automatic functions. This provides clearer rules for when to alert SCC operators and by that creates a more deterministic system.
- The concept of ODD, DNT and fallback to describe the different properties of the operational domain and what functions are required to handle the complexity.
- The division of DNT into OE-DNT and CS-DNT to specify what functions are handled by automation and what functions are expected to be handled by the operator.

- Five levels of autonomy that corresponds to the five main ways to divide responsibility between humans and automation on an autonomous ship.

Thus, ship autonomy needs to be looked at as a multidimensional property, encompassing both operational factors (Operational Design Domain) and the implemented automation and crew support (Dynamic Navigation Task). These concepts are in themselves multi-dimensional, covering respectively temporal and functional design limits as well as combining crew and automation system responsibilities.

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