Definitions for Autonomous Merchant Ships

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Editors and main contributors	Company
Ørnulf Jan Rødseth (ØJR)	SINTEF Ocean AS
Håvard Nordahl (HN)	SINTEF Ocean AS

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Summary

This document contains definitions that are relevant when describing what an autonomous ship is, the context it operates in and the functions it needs to implement to operate safely. Section 1 gives a brief introduction, some high-level definitions and explains the relationships between the groups of definitions. Section 2 defines the different autonomous ship types. Section 3 defines the ship's support systems and its general operational context. Section 4 defines automation levels and autonomy types as a function of automation level and bridge manning level. Section 5 defines the Operational Design Domain (ODD) and corresponding terminology to specify what the ship can and cannot do and how fall-back procedures are used to handle situations outside the operational domain. Section 6 briefly discusses the use of different autonomy types on the same ship during a voyage. Section 7 gives a functional breakdown of the ship that can be used as basis for describing the ODD or for doing hazard identification. A final section provides acknowledgements.

One should note that definitions in this document implies that an autonomous ship in almost all cases will be remotely supervised from a remote monitoring and control centre and that it rarely or perhaps never will have "Full autonomy", i.e. is completely independent of a human operator.

The information provided in this report is a suggestion to the community of autonomous ship researchers and we hope it can be useful in establishing the necessary standardised definitions.

Terminology and abbreviations used in this document

This section briefly repeats definitions and abbreviations found elsewhere in the document. References to the section or sub-section where the full definition can be found, are included.

Automation: The processes, often computerized, that implement a specific and predefined method to execute certain operations without a human controlling it (sec. 1).

Automatic**:** The system has automation functions that can complete certain operations without human control (sec. 4).

Automatic bridge: Automatic bridge, with crew always on the bridge (sec. 4).

Automatic ship: Ship is supervised by SCC and executes automatic functions (sec. 4).

Autonomy: The system has control functions that can use different options to solve selected classes of problems (sec. 1, sec. 2).

Autonomous ship: Ship with some form of autonomy (sec. 1).

Autonomy Assisted Bridge (AAB): Continuously manned bridge with autonomous control functions (sec. 2).

Constrained autonomous**:** Autonomous control system with defined limits to its freedom of choice (sec. 4).

Constrained autonomous ship: Unmanned ship with constrained autonomous control functions (sec. 4).

Continuously Unmanned Ship (CUS): Crew never on ship, except possibly during emergency recovery (sec. 2).

Decision support: Systems provides decision support information to crew, but has limited automation (sec. 4).

Direct control: No autonomy, possibly decision support and simple automation (sec. 4).

DNT Fallback: Predefined emergency procedure when ODD is exceeded (sec. 5).

Dynamic Navigation Task (DNT): Set of tactical operations supported to operate in ODD (sec. 5).

Emergency Control Team (ECT): Used for PUS or CUS during unexpected emergencies (sec. 3).

Fully autonomous**:** Autonomous control with full flexibility and no constraints (sec. 4).

Fully autonomous ship: Unmanned ship with fully autonomous control functions (sec. 4).

Local Monitoring Services (LMS): Optional local services for autonomous and other ships (sec. 3).

Maritime Autonomous Surface Ship (MASS): Common terminology for any autonomous ship (sec. 2).

On-board Control Team (OCT): Used for PUS (sec. 3).

Operating Design Domain (ODD): Definition of system's operational area and constraints (sec. 5).

Periodically Unmanned Bridge (PUB): Ship is unmanned, e.g. during night in calm weather (sec. 2).

Periodically Unmanned Ship (PUS): Ship unmanned, but crew can enter ship for demanding operations (sec. 2).

Remote control: Ship is remotely controlled from SCC (sec. 4).

Ship: Merchant vessel with own propulsion (sec. 1).

Shore Control Centre (SCC): Owner's centre for monitoring and control (sec. 3).

Shore Sensor System (SSS): Optional shore sensor systems for autonomous and other ships (sec. 3).

Unmanned: Without crew controlling the ship, but ship may not be autonomous, i.e. can be remotely controlled (sec. 2).

Vessel Traffic Services (VTS): Shore service for monitoring of ship traffic in certain defined areas.

1 Introduction and background

Autonomous and unmanned ships are new concepts that will challenge the conventional methods for designing, testing and approving ships and their systems. It will to some degree also require a new mindset. The definitions provided in this report is intended to help in this process and is based on a conceptual development chain as illustrated in Figure 1. This figure is inspired by the structure of and ideas in the US standard taxonomy for automated road vehicles, published by the Society of Automotive Engineers as SAE J3016 [5].

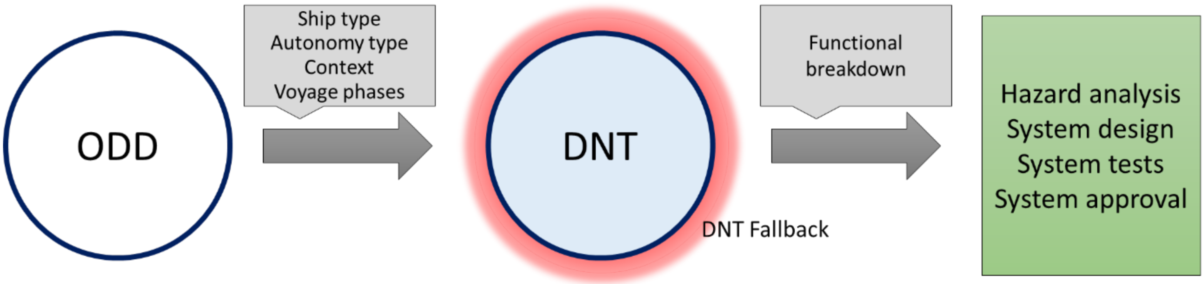

Figure 1 – Relationship between groups of definitions

The Operation Design Domain (ODD) is a definition of the environment the ship operates in, what equipment it has and what operations it performs. This is the baseline for the design. The ODD must be translated into a Dynamic Navigation Task (DNT) that specifies the necessary functionality the ship and its support systems require. Note that the term "Dynamic Driving Task" (DDT) from the SAE standard has been replaced by DNT here, to reflect that our domain is a ship. The ODD and DNT are discussed in section 5. Finally, a systematic functionality breakdown is one of the tools used in the further analysis and design of the system. This is briefly discussed in section 7.

There is no generally accepted definition of "ship". Different texts provide their own definition dependent on the subject matter[6]. In this report, ***ship*** is defined as a vessel with its own propulsion and steering system, which execute commercially useful transport of passengers or cargo and which is subject to a civilian regulatory framework. This implies that it will be of significant size and length, and that it has a relatively high potential for causing damage if the operation fails in some way. Any minimum size will depend on the legislative framework, e.g. Norwegian law generally defines vessels above 15 m as a ship [1]. Military and research vessels normally fall outside this definition.

An ***autonomous ship*** is a ship, per the above definition, that has some level of automation and self-governance. ***Automation*** is used as a general term for the processes, often computerized, that make the ship able to do certain operations without a human controlling it. ***Autonomy*** is the result of applying "advanced" automation to a ship so that it implements some form of self-governance, i.e.

that it can select between alternative strategies without consulting the human. A common autopilot, although being automatic and possibly quite advanced, will not provide autonomy by this definition. It will always follow a given heading.

Other definitions in the document are based on the break-down of ship autonomy shown in Figure 2. Autonomous ship types will be defined in section 2. Operational autonomy level, bridge manning levels and ship autonomy types are defined in section 4.

Figure 2 – Development of other terminology and definitions

The emphasis in the report is on bridge automation. The reason for this is that engines and other technical systems have already been extensively automated and that most ships now operate with periodically unmanned engine spaces, although an engineer will be required by current legislation. This means that the next level of automation needs to focus on the navigation and bridge functions. However, this does not mean that other ship functions are "trivial". Technical operation and maintenance will be a major challenge for fully unmanned ships. Section 3 will discuss possible alternative manning arrangements, both for engine and bridge.

During our work in different R&D projects on autonomous ships, we have seen a need to provide standardised definitions for the concepts that are commonly used in descriptions of autonomous ship technology. In this document, we will cover higher-level definitions, mainly in the semantic and process layer, of what is often called an Information System Architecture [1], [3]. Figure 3 shows the main components of this type of architecture. These levels are the link between the information system implementation and the problem description domain. Thus, these definitions need to be identical, or at least uniquely convertible, to corresponding definitions in the problem domain. The definitions in this document are to a large degree based on the system architecture specification for MUNIN [10], [11].

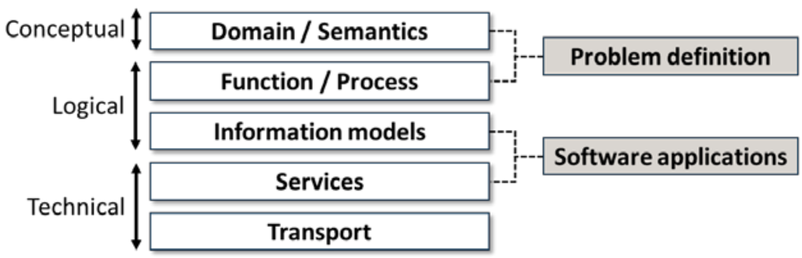

Figure 3 - General information system architecture components.

The definitions are also heavily influenced by the US standard for automated road vehicles, SAE J3016 [5]. There are significant differences between road vehicles and ships, so the standard cannot be directly applied. However, the general concepts and structure of definitions are very similar.

The following chapters are roughly organized from high-level semantics to function level. It is not complete, but we have included suggestions for the definitions that we believe are most immediately needed. Definitions of terms are given with the term in ***italic and bold***, together with the textual description. A short version of the definition can also be found in the definition section with a reference to where the actual definition is located.

2 A taxonomy for unmanned and autonomous maritime vehicles

2.1 Unmanned and autonomous

The terms "autonomous" and "unmanned" are used in different texts, sometimes to mean the same thing and sometimes used individually with different meanings in different texts. We propose the following principle for using terms:

- ***Autonomous*** means that the ship can perform a set of defined operations with no or reduced attention from a bridge crew. This does not necessarily mean that no human is present. Further details on the division of tasks between system and human can be found in section 5 and are illustrated in Figure 7.
- ***Unmanned*** means that there is no human present on the ship's bridge to perform or supervise operations. Crew may still be on board the ship.

This is not fully compliant with some existing uses of the terms, e.g. for underwater vehicles. However, they are in line with the general meaning of the concepts autonomous and unmanned.

2.2 Autonomous ship types

A taxonomy for the different types of autonomous maritime vehicles is shown in Figure 4. Boxes with a black outline represent terminology that is in common use today. Others represent suggested terminology. The green and yellow boxes contain definitions commonly found in surface and underwater autonomous vehicle literature. Note that the term vehicle is used in this literature, as they generally cannot be called ships. The blue boxes are the suggested definitions for the *autonomous ship types.*

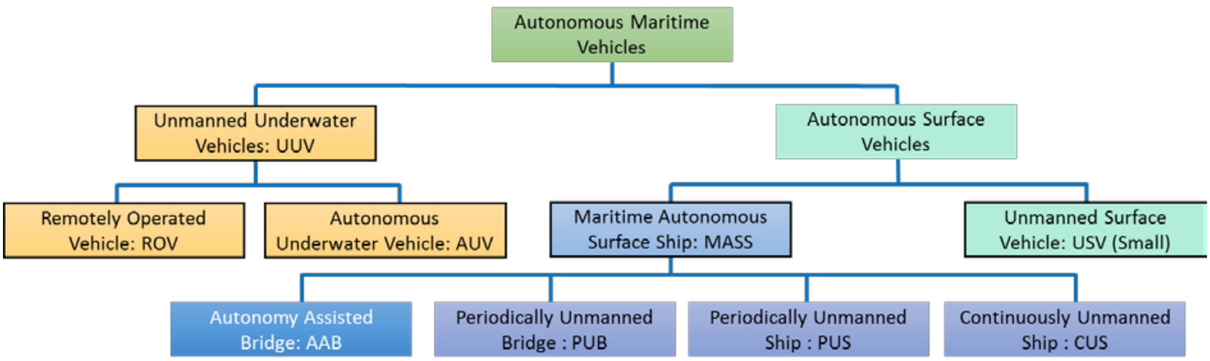

Figure 4 – Classification of autonomous maritime systems and autonomous ship types

Maritime Autonomous Surface Ship (MASS) has already been suggested as a general term for autonomous ships [4]. This needs to be subdivided into different classes that have different impact on operation and legislation:

- ***Autonomy Assisted Bridge (AAB) /Continuously manned bridge*:** The ship bridge is always manned and the crew can immediately intervene in ongoing functions. This will not generally need any special regulatory measures except perhaps performance standards for new functions on the bridge.

- ***Periodically Unmanned Bridge (PUB)***: The ship can operate without crew on the bridge for limited periods, e.g. in open sea and good weather. Crew is on board ship and can be called to the bridge in case of problems.
- ***Periodically Unmanned Ship (PUS)***: The ship operates without bridge crew on board for extended periods, e.g. during deep-sea passage. A boarding team enters or an escort boat arrives to control the ship, e.g. through the port approach phase. For regulatory purposes, this would probably be the same as CUS (See next).
- ***Continuously Unmanned Ship (CUS)***: The ship is designed for unmanned operation of the bridge at all times, except perhaps during special emergencies. This implies that there are no one on the ship that are authorized to take control of the bridge, otherwise, the ship would be classified as PUB. There may still be persons on the ship, e.g. passenger or maintenance crew.

These definitions are included to provide a suggestion for common names for the different autonomous *ship* types. As noted above, these types will overlap with regards to regulatory and possibly other issues. This is made explicit in the definition of the bridge manning levels in section 4.3, which is a more precise and unique definition.

3 The autonomous ship system context

3.1 The general autonomous ship context

The context diagram shown in Figure 5 applies to a general autonomous ship (MASS) and its relationship to external entities. The orange coloured entities represent the autonomous ship system, including a Shore Control Centre (SCC), an On-board Control Team (OCT) and an Emergency Control Team (ECT).

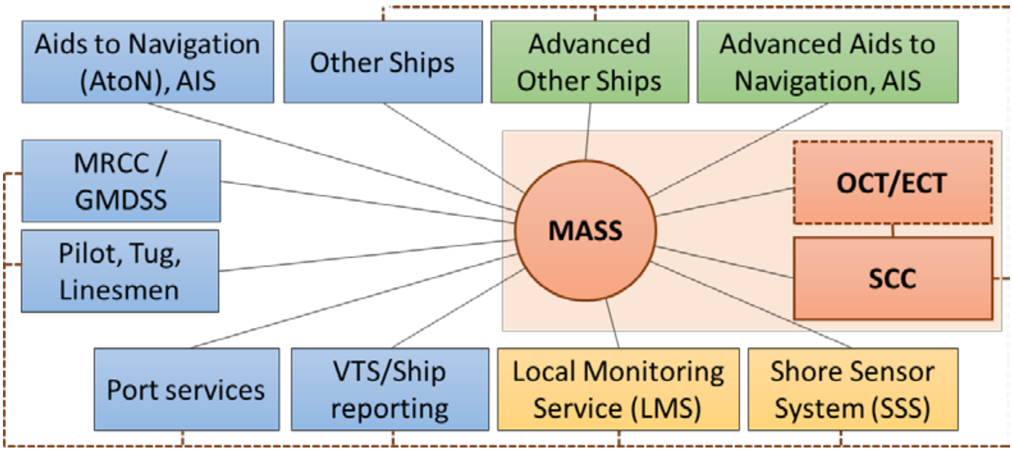

Figure 5 – Context diagram for autonomous ship

The ***Shore Control Centre (SCC)*** will almost certainly be present for all autonomous ships, except for the AAB class. It will be used partly as a backup in case the ship encounters unexpected events, partly to reduce the required complexity of on board detection and control systems and partly to satisfy legal requirements that some human is in control of the ship. The SCC was analysed extensively in the MUNIN project [12] and the conclusion was that it would be very challenging to design a general autonomous ship system without a continuously manned SCC. The SCC, when in control of the ship, will take over the responsibility of the ship's master and any other persons with defined roles on board, see sec. 3.4. It will be operated by or on behalf of the ship owner as a private entity. A SCC will in the general case be expected to serve several ships to make best use of its resources. One ship can also in principle be served by different SCCs, e.g. residing in different time zones. However, this may cause legal problems, and needs to be investigated further.

Note that a SCC does not have to reside on shore. One example is a convoy of unmanned ships being shepherded by a manned escort vessel. In this case, the SCC could be on the escort vessel. The term Shore Control Centre is still suggested as it has been used extensively in literature and because it clearly conveys the meaning that the centre is not on board the autonomous ship.

The ***On-board Control Team (OCT)*** and ***Emergency Control Team (ECT)*** are mobile teams that may enter the ship in special cases, e.g., for taking the ship into or out of port (PUS) or after a critical breakdown of some ship systems. An alternative is to directly guide the ship from an escort vessel or a local shore control centre. In this case one will most likely look at this as a transfer of responsibility from the main SCC to a local SCC, on land or on the escort vessel. The OCT is only appropriate for the periodically unmanned ship (PUS) systems, where a crew is expected to take over control in certain phases of the voyage. This was part of the voyage concept investigated by MUNIN.

The blue boxes represent common maritime entities that any ship *must* relate to. These are:

- ***VTS/Ship reporting***: Vessel Traffic Services or Ship Reporting Areas where the ship needs to contact a shore operator for guidance or reporting.
- ***Aids to Navigation (AtoN) and AIS***: Systems that provide the ship with real-time information about the fairways or other ships. AtoNs are normally visible only, but may include radar reflectors. Virtual AtoNs can be transmitted as AIS messages.
- ***Maritime Rescue Coordination Centre (MRCC)*** **and** ***Global Maritime Distress and Safety System (GMDSS)***: These are radio services that are used for ships in distress or emergencies. The autonomous ship may need to use these services and are also required to respond to them.
- ***Other ships***: The VHF data communication system as well as AIS can be used to communicate with other passing ships.
- ***Pilots, tugs and linesmen:*** will also communicate with the ship to provide mandatory or requested services.
- ***Port Services***: Logistic and supply services in port will also have to be arranged. This includes any automatic mooring systems as well as electrical connections.

Dependent on geographic location and type of ship, there may also be other external entities to relate to.

3.2 Optional context components

These are tentative definitions that are included in this document to highlight some future possibilities in technical arrangements supporting autonomy at sea or even more advanced ship monitoring and shore support for conventional ships.

The green boxes represent variants of the blue that *may be* available:

- ***Advanced other ships*** may use more advanced digital communication systems, e.g. based on VHF Data Exchange System (VDES) that allow them to send or receive more information about intentions and status.
- Similarly, ***Advanced AtoNs or AIS*** base stations may be equipped with equipment that allows them to send more information to autonomous or advanced ships, e.g. including waves, current, wind or other parameters.

The yellow boxes represent optional shore infrastructure in areas where the autonomous ship operates:

- ***Local Monitoring Services (LMS)*** which *may be* an automated and voluntary information management system in certain port or high traffic areas. This could be useful for distributing information about current traffic and weather conditions to the autonomous ship or for sending information about autonomous ship activities to other vessels in the area, including leisure and fisheries.
- ***Shore Sensor System (SSS)*** may be used to complement or partly replace ship sensors for operations that are localized to areas where sufficient shore coverage is possible. This can give benefits in better instruments, better locations or for overlapping sensor coverage. This would probably be integrated in the LMS.

3.3 Division of responsibility in autonomous ship systems

Most MASS will have mandatory ship communication facilities on board, although other arrangements can be envisaged. If the ship carries communication equipment, it must be linked to the SCC to facilitate voice communication with other ships or shore entities when the bridge is unmanned. However, as the SCC often will be located on land and thus have access to high capacity communication lines, it may also be useful to connect the SCC directly to other shore entities or even ships via digital communication, e.g. over internet or satellite connections. In Figure 5, this is illustrated as a dashed network extending from the SCC.

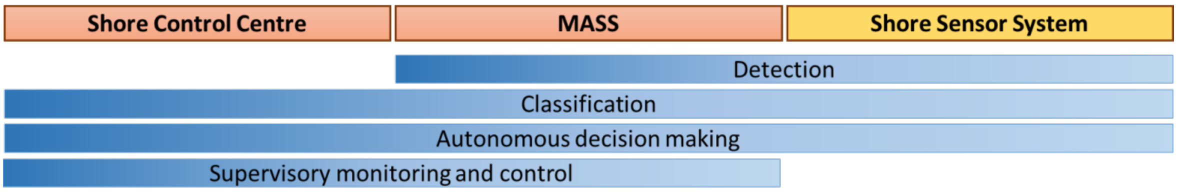

Figure 6 – Possible division of functionality and responsibility in autonomous ship system

If there is a shore sensor system or possibly a local monitoring service available, there is also a possibility to implement different parts of the system functionality in these. Particularly obstacle detection may be more convenient to do in an SSS. Some functionality configurations that may be possible are illustrated in Figure 6.

3.4 Shore control centre roles

If an autonomous ship is to satisfy equivalences to current manning rules, certain roles will likely have to be implemented in the SCC. Exactly what these roles are, must be agreed on by the relevant flag state authorities, but they will likely at least be the following:

- ***Master***: Person on overall charge of the ship. One may also include ship security officer duties in this role.
- ***Chief engineer officer:*** Person in overall charge of the mechanical propulsion and the operation and maintenance of the mechanical and electrical installations of the ship.
- ***Officer of the watch (OOW)***: Person that at any time is responsible for monitoring the ship and intervening if needed.

As described in [7], there are several ways these roles can be implemented in the SCC. This will, e.g. be based on the number of ships under control of the SCC, general flag state requirements etc.

4 Definition of autonomy for ships

4.1 Other definitions of autonomy

Autonomy levels, degrees of autonomy and similar concepts have been discussed extensively in the literature. A general shortcoming is that most existing classification schemes define a very concrete context for the classification that may not fit other applications, such as autonomous ships. Common assumptions are that there is always a person in the vehicle as for the autonomous road vehicle [5] or that the controlled system always operate without any person on board, but only through teleoperation as in Sheridan's classification [9].

There are also some tentative definitions that directly address ships, see e.g., [8], [17], other transport modes, e.g. [20], [21] as well as other papers that have influenced the definitions proposed in this document, e.g. [18], [19], [22], [24]. In this document, we suggest defining the type of ship autonomy along two axes: One is the *bridge manning level*. The other is the *operational autonomy level*, independent of where the automation functions are implemented, on the ship or somewhere on shore.

4.2 Operational autonomy levels

We propose four operational autonomy levels for merchant ships as described below. These four levels are quite similar to autonomy levels proposed in the other texts referenced above. The main difference being that the manning levels, as far as possible, have been factored out of the autonomy levels.

- ***Decision support*:** This corresponds to today’s and tomorrow’s advanced ship types with relatively advanced anti-collision radars (ARPA), electronic chart systems and common automation systems like autopilot or track pilots. The crew is still in direct command of ship operations and continuously supervises all operations. This level normally corresponds to "no autonomy".
- ***Automatic*:** The ship has more advanced automation systems that can complete certain demanding operations without human interaction, e.g. dynamic positioning or automatic berthing. The operation follows a pre-programmed sequence and will request human intervention if any unexpected events occur or when the operation completes. The shore control centre (SCC) or the bridge crew is always available to intervene and initiate remote or direct control when needed.
- ***Constrained autonomous*:** The ship can operate fully automatic in most situations and has a predefined selection of options for solving commonly encountered problems, e.g. collision

avoidance. It has defined limits to the options it can use to solve problems, e.g. maximum deviation from planned track or arrival time. It will call on human operators to intervene if the problems cannot be solved within these constraints. The SCC or bridge personnel continuously supervises the operations and will take immediate control when requested to by the system. Otherwise, the system will be expected to operate safely by itself.

- ***Fully autonomous*:** The ship handles all situations by itself. This implies that one will not have an SCC or any bridge personnel at all. This may be a realistic alternative for operations over short distances and in very controlled environments. However, and in a shorter time perspective, this is an unlikely scenario as it implies very high complexity in ship systems and correspondingly high risks for malfunctions and loss of system.

Note: The above levels do not refer to the complexity of automation, this is further discussed in section 5.

4.3 Bridge manning levels

The *bridge manning level* has been defined into the three columns in Table 1, where each of the autonomous ship types defined in sec. 2.2 use one or more of these:

- *Manned bridge*: For AAB and PUB, when bridge is manned. This is the "trivial" case where most current rules and regulations are expected to apply.
- *Unmanned bridge – crew on board*: For PUB, when bridge is unmanned. One critical issue in this case is that mustering the crew to the bridge will take some time and the ship may need some autonomy both for the unmanned operation as well as during the mustering.
- *Unmanned bridge, no crew on ship*: For PUS and CUS. This is the new situation where the ship may need some autonomy, also to handle connection problems in the case of direct remote control.

4.4 Ship autonomy types

Combining the manning levels with the operational autonomy levels, we can define different types of ship autonomy as shown in Table 1.

Table 1 – Ship autonomy types

	Manned bridge	Unmanned bridge - crew on board	Unmanned bridge - no crew on board
Decision support	Direct control No autonomy	Remote control	Remote control
Automatic	Automatic bridge	Automatic ship	Automatic ship
Constrained autonomous	-	Constrained autonomous	Constrained autonomous
Fully autonomous	-	-	Fully autonomous

Some cells have been marked with a dash to mark that they may be less relevant. As an example, a manned bridge could use very advanced autonomous control technology, but this would likely be used to reduce the need for crew to keep a continuous watch, moving the solution and corresponding approval requirements to the next column, or it would be looked at as an "advanced", but still automatic bridge system, with corresponding lower requirements for the approval process, as crew always are present.

The middle column is also somewhat superfluous as it contains the same ship autonomy types as the rightmost column. However, it is kept here to show that approval requirements may be lower as crew are available on the ship to take control in an emergency. This case is also less sensitive to problems with the ship to shore communication facilities.

Thus, for the time being, the above structure is used as baseline. In future deliberations, it is not unlikely that both issues discussed above will be translated to variations in approval parameters like maximum crew response time, remote communication reliability and similar.

For the continuously **manned** bridge, we have defined two possible types of "autonomy":

- ***Direct control.*** The crew on the bridge is continuously in control of operations, although simple automation, e.g. autopilot, or advanced decision support functions may be in use. This is strictly speaking not an autonomy type, but is included in the taxonomy for completeness.
- ***Automatic bridge.*** The bridge system controls the ship while crew on the bridge continuously monitors the situation and can intervene at any time. The level of automation may be arbitrarily high, but crew is always ready to intervene.

For the fully or periodically **unmanned** systems, there are four autonomy types where the ship must operate reliably without humans on the bridge:

- ***Remote control.*** Same as direct control, however here the SCC is in control of the ship. One can also here argue that this is not really a type of autonomy. However, as communication links normally cannot be made 100% reliable, the ship will in most cases need fallback procedures that can be activated autonomously when communication fails.
- ***Automatic ship:*** Same as Automatic bridge, but again being supervised from the SCC.
- ***Constrained autonomous***. Supervised by SCC.
- ***Fully autonomous***. Not supervised by SCC. This type of autonomy is generally complicated to implement and will also mean that the owner of the ship has less control of its operation. Generally, approval of this type of ship will require major changes in regulations, mainly because there is no longer any equivalence to the master or other officers on board.

Note that none of these definitions implies anything about the complexity of the operation the automation system is supposed to handle. This means that a fully autonomous ship may still be approved for use if the operational domain is sufficiently simple. The complexity of the operation is covered in the operating design domain (ODD) discussed in the next section.

5 Operating design domain

Autonomy as defined in section 4 does not consider the complexity of the operation or of the automation system. It is defined as a combination of bridge manning and automation level alone. To fully describe the systems capabilities, one also needs to describe the operation domain the system is designed to handle. SAE J3016 [3] defines the concept of ***Operating Design Domain (ODD)*** to represent this part of the system description. The ODD defines the problem domain that all control and monitoring functions in the system need to be able to handle. This includes the expected complexity of the operation, the manoeuvrability of the ship as well as the expected contributions from any humans that are on or in the loop.

This means that the ship cannot operate under higher complexity than what is defined in its ODD. It also means that the ship may be restricted to operate only under defined environmental conditions, e.g. related to wind, waves or visibility or specified manning conditions. It also needs to specific the capabilities of all sensor, situation awareness, navigation and other functions. Thus, the definition of the ODD is a critical part of the approval process for the autonomous ship.

Figure 7 illustrates the relationship between the ODD and other parts of the system specification for an autonomous ship. The main elements are:

The ***Dynamic Navigation Task (DNT)*** – adapted from the "dynamic driving task" defined in [3], will be the sum of all tasks that need to be executed by the ship automation system and/or the human operators to handle all foreseeable operational requirements in the ODD. The DDT normally limits the tasks to those needed for voyage execution and does not include scheduling, ship deployment planning and similar logistics related operations. This corresponds to the tasks that are under the ship master's responsibility, including the master's voyage planning.

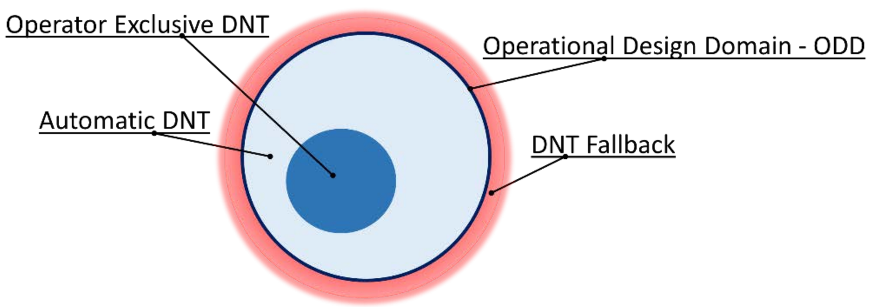

Figure 7 – Illustration of relationships between ODD, DNT and DNT Fallback

The **Automatic DNT** will be the set of tasks assigned to the automation system, on shore or on board. This defines the requirements for sensor systems, object detection and classification, anti-collision systems etc. The **Operator Exclusive DNT** will be the set of tasks assigned exclusively to the operator. This may, e.g. be berthing, tug operations or certain types of heavy weather operations. The operator may take over tasks in the Automatic DNT, but the ship cannot generally take over tasks in the Operator Exclusive DNT. Operator may be the bridge and/or SCC operator.

It is generally not possible to guarantee that the conditions the ship operates under, always are within the ODD limits. Exceptions can occur, e.g., in cases of major technical failures or sudden changes in weather conditions. To handle such cases, a ***DNT Fallback*** [3] must be defined and implemented. The DNT Fallback should take the ship to as safe a situation as is possible under the given circumstances ("Minimal risk condition" [3]). This will consist of different strategies, dependent on the operational condition. Normally, one can assume that the DNT Fallback will be updated from the SCC before the ship's operational context changes significantly.

The approval for an autonomous ship would first need to consider the ODD against the intended operation and the equipment and support systems available to the ship. Then the DNT and the DNT Fallback need to be considered against the expected complexity of the ODD, including any relevant failure modes of the ship or its systems. The distribution of the DNT between automation and operator is of particular importance as this has a great impact on the complexity of the automation system and the reliability of the total system (see also Figure 1).

6 The autonomous voyage phases

During a voyage, the autonomous ship will normally employ different types of autonomy during different voyage phases. This is illustrated in Figure 8 for the three main autonomous ship types.

The codes used are:

- *OCT*: On board Control team
- *ECT*: Emergency Control team
- *DIR:* Direct Control
- *AUT:* Automatic Bridge or Automatic Ship
- *RC:* Remote Control (Direct)
- CA: Constrained Autonomous

	Leave berth	Port depart	Sea passage	Exception	Sea passage
Periodically Unmanned Ship	OCT AUT/ DIR	OCT AUT/ DIR	CA	ECT DIR	CA
Periodically Unmanned Bridge	Manned AUT/ DIR	Manned AUT/ DIR	CA	Manned DIR	CA
Continuously Unmanned Ship	AUT	RC	CA	RC	CA

Figure 8 – Different autonomy type in different voyage phases

The example voyage phases are the following (from left to right):

1. *Leave berth*: Fine manoeuvring as the ship disengages mooring and leaves the berth. For an autonomous ship, this will probably use local position reference systems and a track control system similar to dynamic positioning.
2. *Port depart*: The first part of the voyage will normally be through relatively dense traffic, including other ships as well as leisure craft, and possibly shallow water regions and generally restricted maneuverability. As it is close to shore with easy access to high capacity and low latency communication, various forms of remote control may be used.
3. *Sea passage:* This is normally a relatively simple operation when there are few ships around and if the weather is reasonable. Constrained autonomy would be a suitable mode to use here.
4. *Exception:* This may be heavy weather periods or situations where technical errors hinders normal operation of the ship. In the first case, it may be necessary to use remote control. For PUS, one may need to deploy an Emergency Control team (ECT), if the problem is too severe for remote control.

The rows under the voyage phases show how different autonomy modes *can* be used for different types of autonomous ships. For a periodically unmanned ship one would probably use On-board Control Teams (OCT) during port departure and fully unmanned operation at high seas. The periodically unmanned bridge will use crew on the bridge in more complicated operations, and unmanned operation during sea passage. These are only examples and other strategies may be used.

7 Functional decomposition

The final part of the definitions for autonomous ships is a general breakdown of the functions that must be performed on a ship. In MUNIN, this was used as basis for hazard identification analysis [23] as well as for providing a reference in the SCC for functions that needs to be monitored and controlled.

The work on a standard functional breakdown started in the Flagship project that proposed a structure with 8 main groups and 125 sub-groups [12]. This was used in a central alert management system to connect technical alarms to functional consequences. The breakdown was based on the description of tasks in STCW [13], descriptions from a more technical hierarchy used in the DNV GL class management systems [15] and an earlier functional breakdown from the ATOMOS project [16].

MUNIN processed the above inputs and produced a two-level structure with 10 main groups and 40 elements on the second level. The structure is shown in Table 2. The “Use” column specifies if the entry is applicable for the unmanned ship (US), for the SCC, or not for an autonomous ship at all (n/a). These are indicative classifications and may change between different unmanned ship systems.

Two levels of breakdown are thought to be necessary and sufficient for ship monitoring and functional classification in the context of MUNIN. The number of elements in a sub-group may be added to, if functions are needed that cannot be mapped to current sub-groups.

Table 2 – MUNIN Main function groups and sub-groups

Main group	Sub-group	Use	Description
1. Voyage			
1.1	**Plan**	SCC	Create and maintain a voyage plan based on instructions from shore and known sailing constraints, including planning for port calls and other events.
1.2	**Nautical information**	SCC	Keep track of information related to voyage, nautical publications, weather forecasts, tide tables, port instructions, legislative documents etc.
1.3	**Location**	US	Determine where the ship is and where it is moving in relationship to its voyage plan.
1.4	**Economize**	US	Monitor and assess the operational and economical parameters of a voyage, including fuel consumption, late arrivals etc. Determine corrective measures.
2. Sailing			
2.1	**Manoeuvres**	US	Control the ship during passage to compensate for external conditions, including weather, traffic regulations, other objects. May also include dynamic positioning.
2.2	**Interactions**	US	Manage direct interactions with other ships, pilot boats, tugs, berths, locks etc.

Main group	Sub-group	Use	Description
2.3	**Nautical communication**	US	Communicate with other ships and shore, e.g., reporting areas or VTS. Including updates to MetOcean.
2.4	**Anti-collision**	US	Detect and avoid other objects in the vicinity that may be a danger to the ship. Use COLREGS where applicable.
2.5	**Anti-grounding**	US	Avoid groundings by keeping to safe channels with sufficient air and sea draft and sufficient distance to land.
3. Observations			
3.1	**Weather**	US	Assessment of weather related environmental factors that can impact the ability to execute voyage plan and to manoeuvre, including, e.g., icing and ice.
3.2	**Visibility**	US	Assessment of factors that impact the possibilities to detect other ships, objects, waves, land, aids to navigation etc. Also linked to anti-collision functions.
3.3	**Objects**	US	Detect and observe objects that are important for other ships and services, such as dangerous floating objects, life saving devices, signal flares, man over board etc.
4. Safety/emergencies			
4.1	**Safety communication**	US	Monitor GMDSS, communicate with ships in distress. Send emergency messages; communicate with MRCC and ships, EPIRBS, portable radios.
4.2	**Onboard communication**	n/a	Public Announcement (PA), General Alarm (GA), UHF radios.
4.3	**Emergency management**	n/a	Distress team, response groups, fire-fighting, smoke divers, first aid etc. Includes man over board (MOB)
4.4	**Emergency preparedness**	n/a	Drills, training, maintain hospital, fire prevention, fire patrols, life saving devices, escape routes, lifeboats etc.
4.5	**Technical safety**	US	Fire detection, fire doors and dampers, watertight doors, extinguishing systems.
4.6	**AOS**	n/a	Assistance other ships or persons in distress.
5. Security			
5.1	**ISPS**	US	Monitor access to ship and interactions with entities that can endanger ship's ISPS status.
5.2	**Onboard security**	US	Access control for crew and passengers, network firewalls and data protection etc.
5.3	**Antipiracy**	US	Monitor and control attempts to board or otherwise interfere with ship operations.
6. Crew/Passenger			
6.1	**Passengers**	n/a	Monitor and manage passengers on-board and services for these.
6.2	**Life support**	n/a	Maintain good working and living conditions for the crew and passengers. Ventilation, heating, AC, black/grey water, drinking water, supplies etc.
7. Cargo/stability/strength			
7.1	**Stability**	US	Detect dangers and maintain ship stability and trim. Operate stabilizers, use ballast systems.

Main group	Sub-group	Use	Description
7.2	**Integrity**	US	Observe and maintain water and weather integrity of ship, including ship strength and damage integrity. Monitor and operate hatches and doors.
7.3	**Load and discharge**	n/a	Monitor and manage the loading, stowage, securing and unloading of cargoes.
7.4	**Bunker management**	US	Monitor and manage bunkers and bunker tanks.
7.5	**Cargo condition**	US	Observe and control cargo condition for safe transport during passage.
7.6	**Pollution prevention**	US	Observe and control cargo and ship supplies to avoid and manage discharges and possible pollution, including ballast water handling. Handle dangerous or noxious substances safely.
8. Technical			
8.1	**Environment**	US	Monitor and optimize ships environmental impacts from energy systems and hull in terms of emissions to sea or air including, when applicable, sound emissions.
8.2	**Propulsion**	US	Maintain propulsive functions and efficiency based on available power from engines.
8.3	**Main energy**	US	Produce required energy on shafts to propeller and generators.
8.4	**Electric**	US	Convert and distribute electrical power from generators and other systems.
8.5	**Auxiliary**	US	Control and manage boilers, incinerators and other technical systems not covered elsewhere.
8.6	**Hull equipment**	US	Access, anchoring, lifting, ladders etc.
9. Special ship functions			
9.1	**Other**	n/a	Must be expanded for special ships, e.g., offshore intervention, tugs, dredgers, cable layers etc.
10. Administrative			
10.1	**Operational communication**	SCC	Communicate with ship owner, charterer, cargo owner, ports and agents, weather routing companies or others that may send instructions to ship or require status updates. Including port logs, noon at sea and other reports.
10.2	**Manning**	SCC	Consider the number of, tasks for and working ability of ship crew (STCW)
10.3	**Logs**	US	Keeping mandatory logs on actions taken on board.
10.4	**Mandatory reporting**	SCC	Send mandatory reports to ship reporting systems, port state authorities, ports or other entities.
10.5	**Documents**	SCC	Keep non-nautical ship documents updated: Certificates, ISM documents, manuals …

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[1] http://astat.autonomous-ship.org/

[2] http://nfas.autonomous-ship.org/