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A taxonomy for autonomy in industrial autonomous mobile robots including autonomous merchant ships

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Abstract. The concept of autonomous mobile robots (AMR) has gained much popularity in recent years, particularly in commercial settings where the name industrial autonomous mobile robot (IAMR) is proposed. In addition to automatic guided vehicles and automated mining trucks, IAMR also includes autonomous merchant ships. AMR is an old concept which was first introduced in the 1980s. Although the concept of AMRs is old and broadly used, there is still no common definition of autonomy when mobile robots are concerned. This paper will review some of the most known definitions and develop a taxonomy for autonomy in mobile autonomous robots. This will be used to compare the different definitions of robotic autonomy. This paper will mainly look at industrial autonomous mobile robots, i.e. systems that are designed to operate with a clear commercial objective in mind and which are normally supported by a remote control centre. This means that the robot is not fully autonomous, but to varying degrees dependent on humans in some control and monitoring functions.

1. Introduction

1.1. Autonomous mobile robots in an industrial perspective

The term "autonomous mobile robot" (AMR) has been around at least since 1984 [1] and should be obvious and self-explanatory. The first autonomous mobile robots were developed in the 1980's for research and education and later for scientific mission, e.g. in space or far under ice where it is necessary to have a certain degree of autonomy to handle fully or partly missing communication facilities. Around 1995 some companies started to test the technology in commercial applications, e.g. for supermarket floor cleaning [2]. This could be said to be the dawn of the *industrial* autonomous mobile robot (IAMR). We define an industrial autonomous system as *an autonomous unit, or a collection of such, that can operate safely and efficiently in a real world environment while doing operations of direct commercial value and which can be manufactured, maintained, deployed, operated and retrieved at an acceptable cost relative to the value it provides* [3]. This distinguishes industrial autonomous systems from many academic, space and military projects in that industrial autonomy is directly linked to commercial value creation as well as significant operational hazards.

A special version of the IAMR is the Maritime Autonomous Surface Ship (MASS) [4]. Although it is called an autonomous ship, it does in reality consist of the autonomous ship, normally a remote control centre (RCC), and other support systems, such as automatic mooring systems, position reference systems and so on. Thus, MASS could more correctly be used as an abbreviation for "Merchant Autonomous Ship System," also to highlights that MASS apply to merchant ships and not to, e.g. military or small research type vessels.

1.2. The availability of a Remote Control Centre (RCC)

The use of remote control centres is a common feature for almost all IAMR. High asset value, important commercial interests and often a high damage potential related to accidents will make most operators require that there is a remote monitoring and control function to safeguard their investments. This means that there will be humans in the control and monitoring loops for IAMR. This has two important consequences:

1. If these systems are to be defined as autonomous, we will need a definition of autonomy that goes beyond the idea of being fully independent of humans.
2. The quality and design principles for the Human-Automation Interface (HAI) will be an essential property of the IAMR.

The availability of human operators in the RCC also has an important function in managing the safety and cost of IAMR: The automation system does not have to be able to handle absolutely all situations the IAMR can encounter. If an RCC is available, one can use the human operators to assist in unusual or complex situation. This reduces the cost of implementation of the sensor and automation systems and simplifies testing and approval of the IAMR. However, this requires a high focus on the quality and design of the HAI as timely and correct human intervention will be essential for safe operation of the system.

1.3. IAMR needs a license to operate

Most IAMR will need some form of license to operate. For MASS, this involves approval from its flag state. This approval has to be in accordance with international rules set by the International Maritime Organization (IMO) to allow operation in international or other nations' territorial waters. For other types of IAMR, one will at least see that national Health, Safety and Environmental (HSE) regulations will set strict safety goals for the IAMR.

This means that an IAMR must be associated with an "operational envelope" [5] that defines exactly what the IAMR is able to do and what it is not able to do. If this is not defined, it may be impossible to test the system against safety performance criteria and, thus to issue the necessary license to operate. The implication of this is that an IAMR needs a certain level of determinism in its automation to be able to define its operational envelope.

1.4. Automatic or autonomous

AMR represent a high-growth sector in robotics and automation industry. Broadly speaking, AMR is any robot that can understand and move through its environment without being continuously overseen or controlled by an operator. It is assumed that the environment is not completely known and mapped, and that unmapped obstacles may appear during the mission. Thus, AMR need a set of sensors that enable them to understand and interpret their environment, which helps them to perform their task in the most efficient manner, navigating around fixed obstructions (building, racks, work stations, etc.) and variable obstructions (such as people, lift trucks, and debris).

The automated guided vehicles (AGV) have been moving things around on behalf of humans for more than half a century. They have become a familiar fixture in factories, warehouses, and anywhere there is a need for repetitive material delivery. The traditional difference between AGVs and AMRs is that the AGVs follow fixed routes, usually along wires or magnets embedded in the ground, while AMRs employ sensor systems to find its position and to avoid obstacles. However, when the guidewire is exchanged with a positioning system and sensors are added to avoid collisions, the AGV becomes an AMR, although the exact border is blurred. An example of this confusion are the transport systems that are used in in the St Olav Hospital in Norway that are commonly referred to as "autonomous", while it may also be called an AGV system [6].

Section 2 of this paper will come back to this issue and attempt to provide a definition of automatic and autonomous that can resolve some of these issues.

1.5. Dimensions of automation and autonomy

A well-known framework for defining autonomy levels for unmanned systems is ALFUS [7]. This defines levels of autonomy along three axes, *Mission Complexity*, *Environmental Difficulty* and *Human Independence*. This illustrates that the level of autonomy has to do with more than just human independence, at least the complexity of the mission and environment should be considered. This should also have an impact on the definition of when a system can be seen as autonomous versus only automatic. Several other variants of this "multi-dimensional" approach to autonomy will be discussed in section 4.

1.6. Autonomy for different processes and different mission phases

Large IAMR, like merchant ships complicate the definition of autonomy by having different requirements in different mission phases and for the different system processes. An example of the latter is the "periodically unmanned machinery spaces" that already is allowed on merchant ships. This automates the engine room, but leaves supervisory monitoring to the bridge officers. When discussing autonomy, one tends to focus on navigation. On a ship there are numerous other systems that need automation, such as energy production, fire safety, ballast, and hull integrity. In addition there will be different requirements for autonomy in different phases of the mission. Sailing on deep sea routes with few or no other ships in the vicinity is very different from sailing in narrow channels or in port areas. Thus, a definition of autonomy for MASS needs to take these factors into account.

1.7. Purpose of this paper

There is already a high and growing interest in MASS. Unmanned and autonomous ships have many properties that make them interesting in commercial applications, e.g. lower cost and lower energy consumption, ability to scale down ship sizes to realize flexible and more user oriented transport services and more [8]. On the other hand, merchant ships are internationally regulated through the International Maritime Organization (IMO) and must follow a strict approval regime, involving flag state and classification societies. This makes it important to provide good definitions of what an autonomous ship is and how it is differentiated from more conventional ship types, which also can have a high degree of automation. To provide some guidance in this process, this paper will investigate the following issues:

1. Is there a need to differentiate between autonomy and automation?
2. If so, how to define the difference?

As has been pointed out before, there are several issues that have an impact on these questions, in particular the number of dimensions in the space where autonomy appears, being it related to operation complexity, phases or ship processes. This will be discussed with the help of a simple taxonomy for IAMR autonomy. This taxonomy will be developed in section 6 and compared to a set of example IAMR described in section 4. Section 5 will give a brief overview of some official definitions of autonomy in the context of MASS.

2. Defining automatic and autonomous

2.1. Do we need the concept of autonomy?

The word “autonomy” is derived from the Greek word “autonomia” which means independent, or more literally, living by one's own laws [9]. The word represents a concept found in different kinds of sciences, like engineering, philosophy, biology and medicine. As far as the engineering etymology is concerned, the word autonomy has been proposed used in order to describe the ability of an engineering system to make its own decisions about its actions while performing different tasks, without the need for the involvement of an exogenous system or operator [10].

Several sources suggest that autonomy as a term should be depreciated. The main arguments are that autonomy has already been given the meaning of "independent of external control", it should not be given a new definition in the context of IAMR and, thus the term should be avoided in professional literature. The exception may be systems that are truly and fully independent of any operator, including the need for any human fallback solutions. The American Society of Automotive Engineers (SAE) is one of them, and proposes to use the term "automated driving" [11]. The Central Commission for the Navigation of the Rhine (CCNR), which is the most important European organization for inland waterways, has adopted a strategy similar to SAE and currently uses "automated navigation" rather than autonomous [12]. Some classification societies have adopted a similar position (see section 5).

On the other hand, automation in the area of IAMR and ships in particular, is already far advanced and fully incorporated into existing international legal instruments. Traditionally, when new forms of automation emerges, e.g. as the automatic radar plotting aid (ARPA) in the 1960's, they are usually deployed with no need for change in regulations and used to assist the operators. Although, as use and experience evolve, some of these systems are eventually used to reduce crew sizes, and regulations are updated accordingly. The situation with autonomy in IAMR is very different. The current projects, at least in the MASS sector, aims at controlling the ship without operators directly attending to many critical tasks, although they still have a role in handling difficult situations and in high level monitoring of the system. This is clearly not a fully autonomous operation, but one can also argue that this new state of matters may require a new adjective other than automatic. It will in any case require a new approach to regulations in the maritime sector, something that the regulatory scoping exercise currently under way in IMO is trying to find an answer to.

It is also very difficult to find a good definition that clearly distinguishes automatic from autonomous. No nation, organism nor engineering system is completely free from any type of external control. There is virtually always an external set-point, relationship or other factor that guides the system's actions. Particularly for IAMR, there is absolutely no point in having an autonomous system that does not follow orders or mission plans. Thus, reserving autonomous for this type of "fully independent" operation is meaningless. Thus, it may be better to use the term *autonomous* for the major change in regulatory approaches that fully or partly unmanned operations require. Additionally, autonomous as a concept, has already been taken up in professional texts and it may be better to assign a clear meaning to it, rather than trying to remove it from the vocabulary.

2.2. A definition of automation

A common understanding is that automation includes the execution by a machine agent of a function that was previously carried out by a human [13]. This can concern different control systems for operating equipment in numerous applications such as production, medical equipment, traffic control or buildings to name only a few examples. However, the concept of automation has changed through time. It can mean a simple reallocation of a function from human to machine which is complete and permanent. In that case, the function will tend to be seen simply as machine operation not as automation [13], i.e. as can be seen with automatic elevators. Today, they are just elevators.

The roots of the word automatic are Greek, from *autos* "self" + *matos* "thinking, animated" [9]. It is normally used in several different meanings, e.g. 1) acting or operating in a manner essentially independent of external influence or control, or 2) Acting or done without volition or conscious control; involuntary [14]. *Automatic* was introduced around 1810 in the meaning of "self-acting" [9]. The word *automation* was introduced in the mid-19th century in conjunction with automatic production processes in car production [9].

When discussing the difference between automation and autonomy, it is tempting to use definition 2) above as basis and say that automation refers to a system that will do exactly what it is programmed by the programmer to do, without having any choice or possibility to act in any different way, and stay true to the operators instructions. Its actions are predefined from the beginning and it has no ability to change them into the future. However, this has at least two problems:

1. An adaptive controller, e.g. an autopilot that adjusts its control laws to adjust for variance in the weather or the ship's loading condition, must it be defined as autonomous, as it certainly seems to be more than automatic?
2. Most IAMR is deterministic in the sense that they need to limit its capabilities to an operational envelope and provide testable responses to all critical situations it can encounter, as discussed in section 1.3. Must all these systems be defined as automatic, independent of how "intelligent" they are within the operational envelope?

In general, most computer system must follow its programmed instruction, independent on how adaptable it is. Adaptability can be programmed into a system, e.g. by statistical estimators or by machine learning, that allows the computer program to give responses that seem more variable, but these responses are still limited by the control frameworks that they are programmed into.

A more pragmatic definition of automatic can be found in IEC 60050-351 [15] and in ISO/TR 11065 [16]. With some slight modifications this can be stated as:

> *Pertaining to a process, device or equipment that, under specified conditions, [can] function without human intervention."*

Here we have added "can" before *function* to emphasize that some form of human instruction or supervision is necessary also in fully automated processes and changed to "*device or equipment*" as the two standards use the respective single word in this part of the definition. Automation is defined in
[16] as "*The implementation of processes by automatic means*." The above is also the definition that ISO has proposed to IMO as part of a new terminology for MASS [17].

2.3. A "weak" definition of autonomy

The input document from ISO to IMO [17] also proposes a definition of autonomy that, when generalized to IAMR instead of ships, reads as follows:

> *Autonomous, autonomy: In the context of IAMR, autonomy means that the IAMR uses automation to operate without human intervention, related to one or more processes, for the full duration or in limited periods of the IAMR's mission.*
>
> *Note 1: This definition requires that the operation can be performed without human intervention during the specified time period. This differentiates autonomous functions from conventional automation by requiring that automation that facilitates autonomous operation must be designed and verified to allow it to be unattended during the whole of the relevant time period.*

This definition also addresses the problem of including the multiple internal processes and the different voyage phases that ships and some other IAMR have to consider (see section 1.6).

A similar definition of autonomy can be found in [18] and is in that publication called a "weak" definition of autonomy.

> "*the extent to which a system can carry out its own processes and operations without external control*."

Both these definitions differ from the definition of automatic by requiring that the system *shall* be able to function without external control for a specified time and process. Beer et al. [18] also proposes a "strong" definition of autonomy which require a certain degree of "machine cognition," that will be returned to in section 4.

This differentiation between automation and autonomy allows a clear distinction to be made between the two concepts, although it has some side effects, e.g. that a simple thermostat now could be considered autonomous instead of just automatic!

3. Some examples of autonomous or automatic systems

Section 4 will go through some of the different factors that have been used to differentiate autonomy from automation in the literature. To provide a reference for the use of these factors, this section will provide four examples of IAMR systems that represent some typical classes of applications.

3.1. A ship autopilot

An autopilot is similar to a car cruise control, but is able to keep a constant heading as well as a constant speed. A modern ship autopilot will have adaptive control algorithms to better control the ship with different under-keel clearance, in different loading conditions and in different weather conditions. Autopilots may also make use of fuzzy control and other typed of "artificial intelligence" type technology [19] to provide parts of this adaptability. More advanced control criteria, in addition to minimizing speed and course variance, may be to minimize fuel use and rudder movements.

According to the weak definition of autonomy, an autopilot can be said to be autonomous as it can perform the relevant control processes independently of human supervision. The crew will attend to other processes, such as lookout, when the autopilot is engaged. However, the crew is still required to stay on the bridge to intervene if something goes wrong.

3.2. Automatic guided vehicle

In this paper we will use the AGV system at St. Olav's Hospital in Trondheim as example [6]. This is operating based on visual navigation and has anti-collision detectors as well as facilities for controlling doors and elevators. It can be operated without human control, although there is an operations centre that intervenes when needed. The robot is relatively simple-minded and will not try to avoid obstacles but will either automatically ask persons to remove themselves or call the operations centre when the obstacle remains. Then a service engineer needs to assist the vehicle to resolve the problem. Also, this AGV can be classified as autonomous according to the weak definition of autonomy.

3.3. Autonomous mining trucks

Autonomous mining trucks have been in use since 2006 and there is a code of practice for safe mobile autonomous mining in Australia [20]. These trucks are operating in controlled environment and mostly follow pre-planned routes. However, there are sensor systems that can detect other objects and either change the truck speed to avoid collisions or stop the truck. The trucks are normally uncrewed. Also this system will satisfy the weak requirements to being autonomous.

3.4. The MUNIN bulk carrier

The MUNIN project [21] made a concept study of a bulk carrier that was unmanned, but under control of a remote control centre for the deep sea passage between Europe and South America. The ship was manned during port approach and departure. The RCC operators would not normally operate the ship during the sea passage, but could be alerted in case of problems such as bad weather, unknown obstacles or technical faults. The automation system would use radar and visual sensors to detect and avoid obstacles, but it was assumed that this was relatively simple and that avoidance manoeuvres were limited to one or two other ships. Also object classification was mostly limited to identifying other ships, e.g. with the use of automatic identification system (AIS) messages. If this failed, one would rely on the RCC crew if identification was necessary. The MUNIN bulk carrier can also be defined as autonomous according to the weak definition of autonomy.

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4. Automation and autonomy have more dimensions than just human supervision

Section 2.3 suggested a weak definition of automation and autonomy that allows us to more clearly differentiate between the two. One should note that from the regulatory side, this distinction may be the most important: Determining how certain human control processes can be taken over by machines and how to allow the humans to absent themselves during the operation.

However, the example of the "autonomous" thermostat in section 2.3 may indicate that we need a stronger definition of autonomy [18], and this section will go through some of the different dimensions of automation and autonomy that have been proposed as additional qualifying factors.

Table 1 shows how the weak definition of autonomy applies to the four example systems. All system can operate without direct operator attendance. However, for the autopilot this is only to a limited degree as the operator needs to be in the vicinity of the bridge, even when the autopilot is engaged.

Table 1: Environment as qualifying factor for autonomy

	Autopilot	AGV	Mining truck	MUNIN
Attendance	(Yes)	Yes	Yes	Yes

For larger IAMR it is also relevant to talk about different levels of autonomy in different processes and/or for different parts of the mission (see section 1.6). This has different relevance for different types of IAMR, but Table 2 shows how these attributes could be linked to the example systems.

Table 2: Different autonomy levels for processes and mission phases

	Autopilot	AGV	Mining truck	MUNIN
Functions	(All)	Some	Some	Some
Phases	Part	Part	Part	Part

Except for the autopilot, all systems will have different levels of autonomy in different processes. As an example, propulsion system maintenance on most systems will not be automatic, but will rely on periodic maintenance when the vehicle is inactive. This also means that all systems will only be automated in certain parts of their activities.

4.1. Environment sensing and complexity

A common way to define autonomy is to refer to the requirement of being able to sense real-world environment and act appropriately to hindrances that it may experience. One example is the following:

> *"Autonomy refers to systems capable of operating in the real-world environment without any form of external control for extended periods of time" [22].*

When applied to the four examples in section 3, we get the results listed in Table 3.

Table 3: Environment as qualifying factor for autonomy

	Autopilot	AGV	Mining truck	MUNIN
Env. sense	Yes	(Yes)	Yes	Yes

Here, one can argue that the inclusion of operation in a real-world environment does not really add any significant differentiating factor. Any automatic robot, including an AGV, will at least need to detect its position and will normally include some form of anti-collision function that allows it to act, perhaps just stop, based on the environment information.

A certain complexity of the environment could be a more relevant factor and that has been proposed as one of the axes defining autonomy in the ALFUS framework [23]. Here, both environmental difficulty and mission complexity are assigned metrics that are used to determine the "contextual autonomous capability". This allows the users of the framework to assign a "level of autonomy" to the system, but is difficult to use as a binary qualifying factor. Doing the comparison with the examples again, gives us Table 4. Here, the "level of complexity" has been indicated. Note that the mining truck and MUNIN environment are classified as medium complex. They are operating in a relatively controlled environment or in open sea, with limited unexpected obstacles.

Table 4: Environment complexity as qualifying factor for autonomy

	Autopilot	AGV	Mining truck	MUNIN
Env. complexity	Very low	Low	Medium	Medium

4.2. Cognition and planning

The following definition is a further development of the one presented in section 2.3. While the latter definition was described as "weak", the following is described as a "strong" definition [18]:

> *"The extent to which a robot can sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal (either given to or created by the robot) without external control."*

A somewhat weaker variant of this is the following:

> *"autonomous system: system that, perceiving its environment and determining if this affects its goals, takes action to ensure as far as practicable that its goals will be safely achieved" [25]*.

The second definition is more implicit in its requirements to a certain level of cognition. The inclusion of "cognitive functions" is obviously a clear difference from automation and could be relevant for differentiating between automation and autonomy. However, the term *plan* in the first definition poses a problem in that it is not well defined. For an IAMR, it will probably not be allowed to change the provided mission plans, although the IAMR will be expected to execute certain types of limited replanning, e.g. safe avoidance manoeuvres. While this in most cases qualifies as a cognitive function, it is not clear that it represents planning.

Both the truck and MUNIN allow a limited degree of avoidance plans to be made by the system, but it is questionable if this is sufficient to call it planning abilities. The AGV can stop if it encounters problems, but the autopilot does not replan at all.

Applying the idea of planning and cognition to the examples provides Table 5.

Table 5: Planning as qualifying factor for autonomy

	Autopilot	AGV	Mining truck	MUNIN
Planning	No	No	No (Very Low)	No (Very Low)
Cognition	(Yes)	No	Yes	Yes

The argument here is that the AGV only stops if it detects an obstacle and does not attempt to find a solution. The autopilot is to some degree able to adapt to the environment and ship conditions.

4.3. Use of artificial intelligence (AI) and learning

Definitions of advanced forms of autonomy will also commonly refer to the system's ability to learn over time [26]. This is also often associated with the use of artificial intelligence (AI) [27] which is also commonly referred to in conjunction with autonomous systems in general. However, none of the main sources refer to any need to implement learning or AI in today's IAMR.

Currently, it is not trivial to use AI in IAMR due to the general need for a license to operate (see section 1.3), which in turn requires strict test and approval regimes. Many AI technologies, in particular neural networks and deep learning, represent a form of decision making where performance may be difficult to quantify, being reliant on extensive testing and statistical methods. For certain operations, e.g. collision avoidance at sea [28], it can be argued that the possible number of situations that need to be tested for is too large to get sufficient significance levels from testing. This means that it may be impossible to prove that the system works sufficiently well in all situations [29]. Object detection and classification may be an easier task, as there probably are much fewer critical cases to classify and test. It is expected that at least object classification may use, e.g. machine learning in its implementation also in current projects [30]. The criticality of these tasks will obviously vary, dependent on the operational domain and type of IAMR.

In a supervised IAMR, it will be easier to deploy AI technology as one may rely on a human operator to intervene if the AI system fails to find a good solution to a problem. However, this also has implications on the human-automation interface as it introduces uncertainty in when the operator may be required to intervene. This could rule out the use of "constrained autonomy" [31], where it is possible to alert the operator to an intervention, in time for the operator to get sufficient situational awareness before actions are required.

Learning is also a complicating issue for IAMR as the IAMR generally needs an approval to operate based on certified technical performance (see section 1.3). If performance changes during operation, will then the original approval be valid? If it is possible to prove that the overall performance will improve and no previous capability is lost, this should be possible, but this is not trivial. Some recent advances in deep learning point to some possibilities for improved retention of knowledge [32], but even here there is degradation in knowledge retention, dependent on the number of patterns the system is required to recognize. For collision avoidance, this may be an issue due to a high number of distinct situations. It may be less of problem for object detection and classification.

If we apply the concept of learning and AI to the examples, we can tentative get a result as shown in Table 6.

Table 6: AI and learning as qualifying factor for autonomy

	Autopilot	AGV	Mining truck	MUNIN
AI	Yes	No	(Yes)	(Yes)
Learning	Yes	No	No	No

This is a somewhat arbitrary classification, but some autopilots are already using AI techniques, and they also include learning in their very limited scope of "expertise", i.e. they can "learn" a new loading condition for the vessel. The AGV will probably use neither due to its relatively simplistic operation. The mining truck may use AI in certain functions, e.g. object detection, which has also been suggested for MUNIN. It is not likely that either of the latter will use learning in their most critical functions, i.e. object detection, classification and collision avoidance.

4.4. Assigning liability to the IAMR

An interesting approach to the definition of robot autonomy is the following:

> *A system is considered autonomous if it can legally accept accountability for an operation, thereby assuming the accountability that was previously held by either a human operator or another autonomous system [33].*

This is a very distinct definition that captures some of the original concept of autonomy by trying to assign legal accountability to the system. This could be said to be in line with the idea of "living by one's own laws". In practical terms and today, this would not work, unless the autonomous robot can be defined to be a juridical person, which is not likely to happen in the foreseeable future. Generally, legal accountability can only be assigned to a real person or certain types of organizations, and not to machines. For IAMR, the legally responsible is expected to be the owner or the de facto operator of the IAMR.

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5. Some official definitions of autonomous ship

As international shipping is based on internationally accepted legislation and rules, there has been a significant development in suggested definitions of autonomous ship is in the different contexts of authorities, standards organizations and class societies. This section will briefly go through some of the best known definitions.

IMO is the main organization for international regulation and has for the time being adopted the following definition [34]:

> *Maritime Autonomous Surface Ship (MASS) is defined as a ship which, to a varying degree, can operate independent of human interaction.*

ISO [17] has proposed a similar, but somewhat more formalized version which was quoted in section 2.3.

The Norwegian Forum for Autonomous Ships [35] suggested the following definition:

> *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.*

NFAS has later adopted the ISO version of the definition.

Bureau Veritas [36] adopts the strategy of reserving autonomous only for ships that are fully automated.

Lloyd's Register does not define autonomy as such but uses a 7-stage scale to describe autonomy levels [37].

The first level where autonomous appears in the text is at level 4:

> *Decisions and actions at the ship level are performed autonomously with human supervision. High impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them. Data may be provided by systems on or off the ship.*

DNV GL proposes to use the term "autoremote" for any mix of decision making between automation systems and operators, except for fully autonomous ships [38]. An autoremote vessel is defined as:

> *vessel for which one or more key functions are remotely controlled from a remote control centre, possibly by assistance from personnel on board. To support safe and efficient operation of the vessel, the remotely controlled key function(s) is arranged with a defined level of automation ranging from simple decision support to complete automatic control.*

Class NK adopts the principle of full automation to allow calling a *function* autonomous. Furthermore, it does not define autonomous in the context of ships but refer to automated/autonomous operations or tasks [39].

American Bureau of Shipping (ABS) defines autonomy as different from automation by:

> *(An autonomous system) requires a quality of self-governance and freedom from external control or influence. Rather than only predefined actions, the system can choose from the best or most appropriate option and not just follow a predetermined algorithm or script.*

Most of the above definitions allow only parts of the ship functionality to be termed autonomous if it otherwise satisfies the definition, i.e. some operations or tasks may be autonomous, although the ship as a whole may not be.

6. Summary and conclusions

As can be seen from section 5, many of the sources prefer to describe systems as automatic rather than autonomous, defining a number of levels of automation up to full autonomy, which is only used when the system is truly independent of human operators. However, both IMO and ISO propose to use the broader and weak definition of autonomy more or less as it was presented in section 2.3. As was argued in section 2.1, the authors also believe it may be better to accept the term autonomy – also for "semi-autonomous" IAMR, but give autonomy a clearer meaning compared to automatic. This can be achieved by using the definition of automation that was proposed in section 2.2.

As for the definition of autonomy, we would prefer the weak definition presented in section 2.3, but there are also possibilities for qualifying this with other attributes as discussed in section 4. A summary of how the example systems satisfy these attributes is shown in Table 7.

Table 7: Environment as qualifying factor for autonomy

	Autopilot	**AGV**	**Mining truck**	**MUNIN**
Attendance	(Yes)	Yes	Yes	Yes
Function	(All)	Some	Some	Some
Phase	Part	Part	Part	Part
Env. sense	Yes	(Yes)	Yes	Yes
Env. complexity	Very low	Low	Medium	Medium
Planning	No	No	No (Very Low)	No (Very Low)
Cognition	(Yes)	No	Yes	Yes
AI	Yes	No	(Yes)	(Yes)
Learning	Yes	No	No	No

If one assumes that autopilot and perhaps the AGV should be called automatic rather than autonomous, it is difficult to pinpoint one qualifier that clearly adds to the weak definition. The reason for this is mainly that terms like, e.g. cognition and environment complexity are not well defined and do not lend themselves to "binary" definitions like autonomy versus automation. Other attributes may be forthcoming in the future or we may get more accurate definitions of the existing attributes. Until that happens, it may be better to stick with the weak definition of autonomy, combined with the corresponding definition of automation.

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