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# Human Factors, autonomous ships and constrained coastal navigation

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**Abstract.** This is a concept paper making propositions for MASS navigation in national coastal waters. The focus is on human factors and the interaction between automation and operators in a remote control centre, as well as seafarers on conventional ships interacting with MASS. Important element is to understand the hand-over process of command, from automation to humans in control, based on the automation on board the vessel as well as the infrastructure surrounding the vessel.

## 1. Introduction

This is a concept paper making propositions for MASS navigation in national coastal waters. The objective is to provide a non-technical, easy to understand narrative on this matter and how and where humans are envisioned to be involved.

The focus is on human factors and the interaction between the technical automation system and the human operators, not only in a remote-control centre (ROC), but also as seafarers on conventional ships interacting with MASS at sea. An important element is to understand the monitoring-control process as well as hand-over from automation to humans and vice versa.

Autonomous shipping is increasingly coming closer as ongoing projects materialise. Commercial projects such as the Yara Birkeland [1] as well as ongoing research projects have a higher TRL (Technical Readiness Level) level than previous. International MASS voyages are still something for the future awaiting IMO regulations, although some solutions for transoceanic navigation was proposed already by the MUNIN project 2013-2015 [2]. So far this have not led to international regulations. In the meantime, it is important to start concrete work on design of concepts for coastal navigation in national waters. Such work will depend on local features of the nation in question. This paper is looking at the Norwegian context with stretches of open, often exposed coastline as well as confined archipelago navigation, sometimes with heavy commercial traffic as well as leisure crafts and small-scale fishing. The proposed concept will assume unmanned navigation (unmanned bridge) with remote monitoring and (in exceptional situations) remote control of the MASS vessels.

The concept also includes new types of infrastructure presently investigated in the IMAT project (Integrated Maritime Autonomous Transport Systems) funded by the Norwegian Research Council [3]. One element within the IMAT project is to identify the awareness to navigational systems, where the land-based, and space-based infrastructure will be important for building robustness to the MASS



operations. This can be awareness to systems for navigation, for communication, and systems for detection of objects that can be critical in a navigating approach of a MASS sailing from A to B.

Using an ergonomic perspective, the paper will start out by looking at the operator and his or her planning and monitoring tasks in the Remote Operation Centre (ROC). We will then continue to look at the interaction between the automation onboard a MASS and ROC, VTS operators and humans onboard other ships and crafts in the vicinity of the MASS. After having spent some time discussing the work situation in the ROC, we will look at the following phases of a typical voyage: 1) maintenance planning 2) navigation planning 3) cast-off 4) transit along open coast and in confined waters, 5) transit in VTS areas, 6) port approach, and finally 7) mooring. What will be the challenges, and what will be possible solutions, is the questions to be answered.

## **2. The operator in the remote-operations centre (ROC)**

MASS is often mistaken for a synonym to *unmanned ships*. A MASS may very well be unmanned but may just as well be manned with maintenance crew or even navigators, even if the autonomous navigation system will do most of the tedious watchkeeping. But whether an unmanned bridge or not, the MASS will almost certainly be monitored from a remote-operations centre (ROC).

### *2.1. The monitoring processes*

The ultimate goal of MASS may very well be a “say goodbye-and-forget, call-me-if-you-have-a-problem” type of vessel. With a mature technology MASS could work invisibly as transport drones just as elevators transport people and goods today without supervision or monitoring. Some would argue that the asset and cargo value is too large to just forget [4], but the point here is not to “forget” the ship, but instead point to the problem of *active* and a *passive* monitoring.

*2.1.1. Active monitoring.* The MUNIN project envisioned an active monitoring process in an transatlantic voyage, Europe to South America, that was the case conceptualised in that project. We sketched then that one operator was monitoring six different vessels on the open ocean, spending ten minutes every hour looking at key performance indicators at each vessel. These indicators could typically be ship performance (e.g. course, speed, roll, heave, slamming, etc.), environment (e.g. potential traffic conflicts, fishing boats, etc.), weather (wind speed and direction, changes in air pressure, forecast, etc.), engine performance (RPM, vibrations, temperatures in engine, bearings, exhaust, cooling water etc.), energy (batteries, power plants, sun cells, etc.), communication (signal sources and performance, satellite coverage, etc.) to just mention a few [5].

Active monitoring has many advantages. The chance is that many problems can be spotted at a very early stage and even if they appear suddenly the operator will be in the loop with a good understanding of the context and the situation around the vessel.

The backside of active monitoring is that it will be very boring for an operator to monitor perfectly functioning ships on an empty ocean hour after hour, day after day. The risk is that when there eventually is an incident, the operator will be out-of-the loop since long. Much research has shown that humans are not good at monotonous monitoring tasks, e.g. [6]. The risk is that active monitoring soon will drift into passive monitoring.

*2.1.2. Passive monitoring.* As opposed to active monitoring one might envision a ROC designed for passive monitoring where operators are available on call from the ship when the MASS has detected any problem it needs help to solve. Different levels of such “operator readiness” will inform the operators about the expected response time. With their vessel on the open ocean and no other ships within the 30-mile range, operators might be on call to deal with problems from a home station or mobile devise. Or they might be in an office area close to the control room, ready to step in. This will probably be a much more realistic and desirable work situation in the long run. For a sketch of suggested operator readiness levels see Table 1).

**Table 1.** Sketch of possible Operator readiness levels (availability and mental readiness)

Operator readiness levels	Maximum response time	
In control	0	Operator in-the-loop and at control station
High	3 min	Operator should be in-the-loop and close to the control station
Medium	15 min	Operator in the ROC ready to get in-the-loop
Low	1 hr	Operator home on call

The big problem here is the out-of-the-loop performance problem (or syndrome) which leaves operators of automated systems handicapped in their ability to take over manual operations in the event of automation failure [7].

**2.1.3. Time-to-get-in-the-loop.** A major challenge will be to design a human-machine interface (HMI) that allow minimal time to get in the loop. This will in no case be possible instantly, so there will be a need for a grace period during which automation on the MASS must be able to handle all situations, some way or another. If the operator does not respond within this *response time*, that is, before the *response deadline*, the automation will have to solve the situation on its own [8].

The length of such response time and the automation's measures during the period and after an operator has failed to answer the call will of course depend on the circumstances: For instance, in a busy approach operator might be given a very short response time, requiring her to literally sit in front of the control station ready to take control on a very short call, while on open ocean, with no other ships within the 30-mile range, the control room might be unmanned with the operator on call.

If an operator that fails to answer the MASS request for help before the response deadline, the automation will go into a graceful degradation to a fail-to-safe-mode. The fail-to-safe-model will look different depending on the circumstances: in close vicinity of a lee coast anchoring might be the preferred choice; in a densely trafficked fairway hovering or heaving to might be the choice and in open waters drifting might be good enough waiting for the operator to get in touch or the communication to be restored.

The design for such automation will be crucial and will probably need to involve machine learning analysing both large numbers of real voyages with manual and automatic ships as well as simulations with all thinkable scenarios. *Black swans*, the unknown unknowns, will be bound to put us up for surprises for many years to come until MASS automatic behaviour eventually will be mature.

An automated HMI should, based of geographical and traffic information be able to, with some accuracy, predict necessary readiness level for the operator.

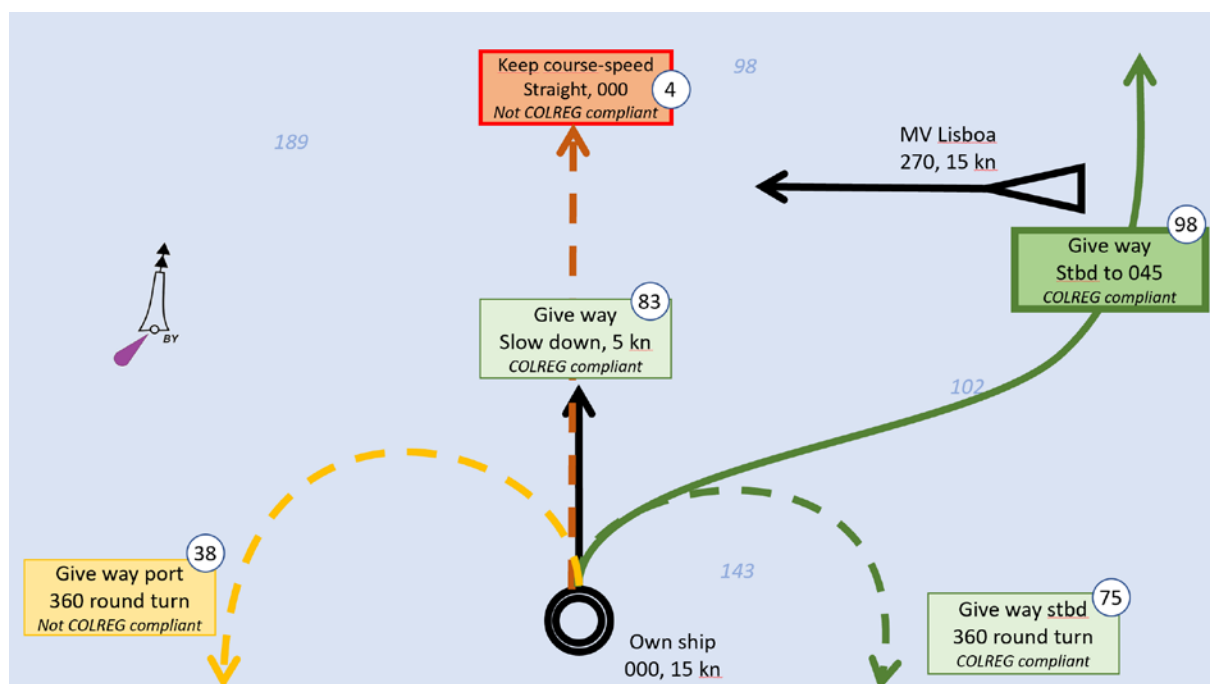
Another big major challenge will be the design of an *automation transparency* allowing this minimal response time.

## 2.2. Automation transparency

To facilitate for the operator to quickly get in-the-loop the automation need to be very transparent about its "thinking". Within artificial intelligence (AI) this field is also called *explainable artificial intelligence* (*explainable AI*, or *XAI*). The purpose is that the results of the solution arrived at by an AI system can be understood by humans. It contrasts with the concept of the "black box" in machine learning where even their designers cannot explain why the AI arrived at a specific decision. Cooperation between agents, in this case algorithms and humans, depends on trust. If humans are to accept algorithmic prescriptions, they need to trust them. For that reason, interpretability and explainability are posited as intermediate goals for checking other criteria.[9] Human users should be able to understand the AI's cognition (both in real-time and after the fact), and should be able to determine when to trust the AI and when the AI should be distrusted [10][11].

This is a very complex and difficult area that will need much research in the future. There has been work on decision trees and Bayesian networks, which are more transparent to inspection [12]. A decision tree is a tree-like flow chart with branches representing different courses of action and rules regarding

which branch to follow. A trivial example could be how to display the multiple courses of action the in a maneuvering situation when a MASS encounters another ship on a conflicting course. Figure 1 illustrates maneuvering decisions in a close quarters' situation where the operator is shown different maneuvering alternatives that the automation is deciding upon. The certainty calculation is color coded and the present decision made by the system is highlighted in green. By doing nothing the operator accepts the automated decision, but she can also click on any of the less preferred alternatives or take manual control. In this figure the own ship in meeting a stand-on vessel from starboard. The automation signals its decision to turn 45 degrees to starboard and pass behind the other vessel. The operator is offered a selection of other possible actions that the automation does not suggest, but that the operator might click on and thus override the automation. Each option has an index score relating to how "certain" the system is of the option.



**Figure 1.** Automation transparency on the operational level might take the form of a decision-tree adapted to the nautical situation. See text for explanation.

More complex, and maybe more realistic situations might borrow methods and techniques from the Explainable AI field. It will be crucial for the decision system of MASSs to behave in a fashion that makes sense for both the operators in the remote-control centre as well as human navigators onboard ships in the vicinity of the MASS. The balance here between information overload and undue simplification for the operator is crucial here and there is an important tradeoff between transparency and completeness of an explanation.

The all-important question is when should the human operator intervene and take over control from the automation? Only when invited, or also in some cases when the automation thinks it is doing OK? What about the timing/response time for handing over control from the automation to humans, should that be a criterion for the different alternatives?

### 3. Maintenance and readiness

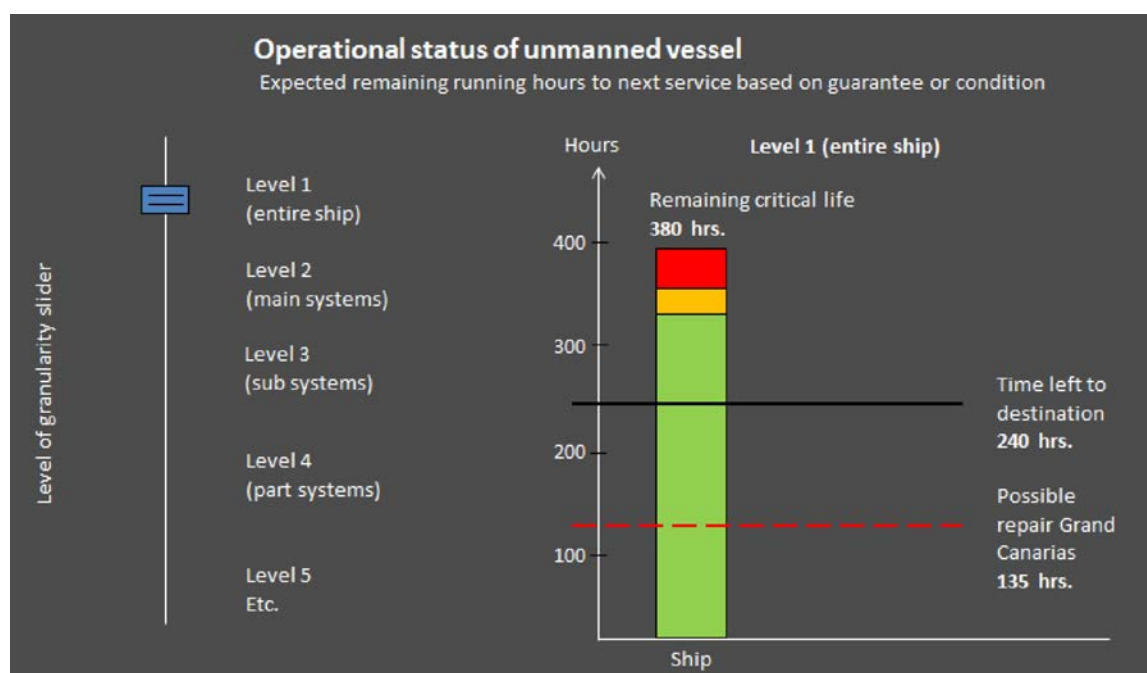
If a MASS is unmanned there will be no-one onboard to fix things that break. Normally the quality of equipment and facilities of modern ships is based on that there is someone onboard that can tighten a leaking valve, change a clogged filter or disconnect and exchange a faulty sensor. If that person is not

available a new strategy is needed. This strategy must rest on *better quality, better maintenance plans and redundancy*.

In the early days of transoceanic airship aviation, the air mechanic could enter the engine gondola during flight for maintenance and repair. In modern aircrafts the type and quality of engines have changed, and flying air mechanics are gone. Should a problem arise there is an engine redundancy. The same development is needed for MASS: simpler, less vulnerable equipment of better quality and three or four-fold redundancy.

### 3.1. Preparing the MASS for voyage

A modern manned ship would normally be constantly kept in running order by its engineers. In the best of worlds, wear and tear would be noted and spare parts ordered and replaced before breakage. A MASS cannot rely on failure finding but will need to rely on time-, predictive- or condition-based maintenance. If anything fails a redundant system needs to take over automatically and update the ship's status indicator. Worst case should lead to a fail-to-safe mode. An early proposal for such an *operational status* indicator from the MUNIN project is shown in Figure 2 [13].



**Figure 2.** The Operational status screen gives an at a *glimpse overview* of the ships present operational status and the remaining time to destination and to possible repair ports for a voyage from Gravesend in the UK to the Orinoco River in Venezuela. By moving the slider to the left the operator can drill down into all sub-systems for a detailed view of their status [13].

In Figure 2 the top status for a ship preparing for a 240 hours long voyage is shown. This case portrayed a transatlantic voyage from the UK to South America with a possible repair opportunity at the Canary Islands 135 hours away. The indicator will show the operator that the ship is prognosed to have more than 300 hours of critical life with full redundancy. The operator can further drill down into the system to see the life expectancy for any group or single component in the ship. This decision support system should be based on time (certified life expectancy), risk (environmental factors for the voyage) and actual condition from sensors onboard. If anything breaks down during the voyage, the indicator will be updated and show the new situation as a base for decision-making. Such a status indicator will be quite complex to develop, but will give the operator a good, *at-a-glance* indication of the mechanical status of the MASS.

#### 4. A human factors perspective

Using an ergonomic perspective, we will in the following take a closer look at some selected phases of a MASS voyage. The purpose is to enlighten the human contribution to the autonomous process and potential problems that might follow.

##### 4.1. Navigation planning

Normally the second mate is responsible for the passage planning onboard a merchant vessel. Her job is to prepare a berth-to-berth voyage plan according to IMO regulation [14]. This means that in an electronic chart (ECDIS) draw up the exact route the ship plans to sail from departure berth (anchorage or quay) to finish. The track must also include such things as cross-track distance (a safety margin on each side of the track) and should be checked for under keel clearance. For instance, should every turn during the voyage include a turn radius based on the ship's particulars. This will be a challenge for the navigation planer in a ROC who needs to keep differ ships particulars apart.

In a ROC this task will be done by the operator or a special group in the ROC working with passage planning. In shuttle traffic this task will reuse old tracks. It will be of importance that the tracks use traffic separated routes so that ships do not regularly will meet head on and need to do evasive manoeuvres. In Norway the Coastal Administration is from 2019 launching a system of (mostly) traffic separated "recommended routes" [15].

Once a detailed voyage plan is entered into the navigation system of a MASS the ship will be able to automatically follow the programmed route.

##### 4.2. Cast-off

The cargo is onboard, status of all systems is go and the MASS is ready to sail. A lot of stakeholder has pressed a green "go" button before we are here: a cargo master have signed off that the cargo is loaded and lashed, an agent responsible for that ship is bunkered, repairs has been made and maintenance personal is off the ship, a port master that the paper work are done and all fees are paid, maybe an inspector from the Safety Administration declaring that the ship is seaworthy and the VTS, if applicable, that the vessel has clearance to leave and that the port approach is free. The operator in the ROC should have an easy and unambiguous way of knowing if everything is ready: a red or a green light. If needed he or she should be able to drill down and see all the different entities giving their clearance.

Before ordering the linesmen or the automatic docking system to cast off, maybe the operator also need to do a manual camera check that there are no kayaks or swimmers around the vessel, that no cable has been forgotten and is still attached to land before hitting the cast-off button. In some cases tugboats will be involved, which will be another layer of communication.

During cast-off the MASS will have the full focus from one of the operators in the ROC. The operator readiness level will be high, in an "*In control*" mode.

##### 4.3. Transit along open coast and in confined waters

Once free of its berth the operator will attach the MASS to its voyage plan, time will be synchronised, the estimated time of departure (ETD) will be changed to the real departure time and all passage times along the route will be updated. Potential conflicts with other known traffic along the route will now be flagged up for the operator, maybe in an itinerary like display [13]. As an example, it could be passing ferry crossings with given timetables or places like the Lepsøyrenna north of Ålesund. This is a 100-metres wide and 1.8 km long dredged channel where you do not want to meet another ship. At some point in advance the system needs to flag up and suggest solutions (stand-on or give-way) for potential conflicts with other ships. Of course, there is no point in doing this days in advance. Instead the system will constantly calculate risks based on other ships *intended routes* [16] within a limited time span ahead of the present position, and of course also include weather data in its calculation. While AIS will give the present position, course and speed of other SOLAS vessels along the path, new systems will be necessary for detecting and tracking small leisure crafts and fishing vessels not equipped with AIS. The



IMAT project propose to set up an auxiliary infrastructure in the Trondheimsfjord in Norway with land radars and cameras to be able to track and predict paths of small crafts and to confirm and identify AIS targets. This fused sensor information will be available for the MASS' navigation system and the ROC operator [3].

Once the MASS has left the port area and entered out into open sea the high readiness level (short response time) of the operator in the ROC is relaxed and if no other traffic or dangers are in the vicinity the vessel may be added to a pool of other ships with the same low readiness level monitored by one operator. The ship will follow the traffic separated coastal route recommended by the Coastal Administration [15]. One may even envision special designated routes intended only for MASS, some distance from the routes recommended for manned vessels. All in the interest of keeping conflicting situations to a minimum. And the MASS's navigation system working as much as possible in "path-following mode". Most modern ships can use the autopilot in a mode where it exactly follows the pre-planned track made in the voyage plan. With good GNSS coverage and 5-10 meters precision, a MASS will be able to navigate automatically through a complex archipelago with no uncharted obstacles. But of course, this is not the case, because there are other fellow mariners as we will see.

*4.3.1. Path-following.* The navigation system of a MASS will have two major ways of working: a dumb path-following mode, and an intelligent, AI governed, automatic or "autonomous" mode (apart from when the operator in the ROC may take manual control). As mentioned above, path-following mode is practiced by many ships already today. The ship uses its autopilot to follow a pre-programmed voyage plan, staying within the set cross-track distance (e.g. 50 metres). If for some reason the autopilot (e.g. strong winds or current) cannot keep the ship within the designated corridor there will be an alarm and the automatic (AI driven) navigation system will take over (or the operator in the ROC). To avoid automation surprises, you would like to keep the ship as much as possible in this path-following mode.

*4.3.2. Autonomous navigation.* When an anomaly occurs for the MASS transiting along its planned voyage in path-following mode the operator in the ROC will be warned and the ship will switch to automatic-navigation mode, meaning that the automatic system (AI governed) will try and resolve the anomaly. If the anomaly is that the ship cannot keep on its designated path due to wind, waves or current, a new path needs to be designed, or if there is another ship on a conflicting course, a COLREG compliant action needs to be taken. The operator in the ROC may or may not be instantly available depending on the operator readiness level. In any case the automatic-navigation system needs to handle the situation in some way and here is where a lot of research needs to be done in coming years. The important thing from a human factor's perspective is how the automatic decisions are flagged up at the ROC, and some examples of this has already been given above.

#### *4.4. Interaction between MASS and conventional ships*

For a foreseeable future MASS will need to coexist with traditional ships with a manned bridge. IMO will need to make a decision on whether a MASS should be identifiable as navigating in "autonomous mode". Such identification could for instance be by displaying a designated flag or light signal. For instance, a *purple* all-around top light has been suggested [17]. An "A" could be added to the AIS symbol. One may argue that a MASS should follow COLREG and behave just like any other ship and therefore do not need to be identifiable as sailing with an unmanned bridge. However, identifying MASS as an automatic ship is not mainly to give her special favours, or that other ships should keep out if her way, instead it can be of interest to broadcast the "limited intelligence" of its automation, and that it always will follow the rules of the road, as opposed to manned ships, where you always need to keep an open mind about intended actions. Ship traffic management (STM) using route intentions will hopefully in the future facilitate conflicting situations such when two MASS meets, the automatic navigation systems on both vessels will negotiate the encounter.



As a MASS transits through the fairways along the coast it is essential that the vessel communicates intentions to other seafarers in the vicinity. This can be done in traditional ways by manoeuvring according to regulations (COLREG), local culture and in exceptional cases by voice transmission. However, manoeuvring in a way that is understandable to other mariners will be of outmost importance. An AI-driven automatic navigation system may well behave in a way that if not understood just because it has the “cognitive power” to look further into the future than the human mind with its limited working memory. In this way it could deal not only with the present conflict situation but also with following situations that a manoeuvre may lead to. This might not always be evident to other human mariners. A trivial example involving just two ships might be a COLREG compliant meeting where the MASS will give-way to a vessel on its starboard side. The automatic navigation system may easily calculate the exact collision position and change to a course just enough to pass behind the stand-on vessel. However, such intention to give way might not be visible enough on the bridge of the stand-on ship. Instead a human watch-keeper would often make an unnecessarily large starboard turn aiming a cable or so behind the stern of the stand-on vessel and then holding this aiming point on the aft while slowly turning back to port until the original course is reached. In this way the give-way vessel might clearly show, both day and night, its intentions of giving way at a cost of some extra distance travelled. This was a trivial example. More complex scenarios with several ships can be investigated in a similar way. However, no matter how many focus groups with navigators, workshops, and automatic randomised simulations that are done to help coding this form of automation transparency we must acknowledge that life will always surprise us with the unexpected. The conclusion being that an automatic navigation system must be programmed to show its intentions in a human-readable way.

#### 4.5. VTS areas

In five areas along the Norwegian coast the Norwegian Coastal Administration has set up Vessel Traffic Service (VTS) stations. The underlying policy is that the Norwegian state grants permission for a ship to traffic its waters and ships entering the area will need to report on arrival and its intended route to the port or through the area. This reporting is today done by VHF voice call, but could, in the future, also be done automatically by digital messaging. An argument against this is that the traffic situation will be less transparent when other ships no longer hear each other reporting on the designated VHF traffic channel. However, STM and transmission of “route intentions,” as mentioned before, might be a solution.

VTS operators spoke to has been very clear that they do not want any extra responsibility for MASS [18]. They want no “emergency stop” button for a MASS transiting its area. Instead they want to be able to call a MASS by voice radio just like any other vessel. Here we have a potential problem: as long as VTS works *analogue* (by manual voice over radio) and do not use *digital* means (as in digital communication and automatic clearance handling and recommendations) we might have a problem that will need much manual handling by operators in a ROC. But eventually this hurdle will be overcome and VTS services will be digital and more automatic.

#### 4.6. Port approach

As the MASS approaches port another set of “green lights” will have to come on from much the same stakeholders as was mentioned in the Cast-off section of this paper. The agent will acknowledge that all is ready, tugs, cranes supplies etc. and the port master that the ordered dockside is available to the right length. If linesmen are needed, they too will acknowledge and someone will need to check that wind, tide and currents are within the envelope the vessel can cope with. When entering a port like Trondheim, for instance, there is a lot of local information that must be considered and that will not be available in nautical charts or publications. Also, the port has a *port control* (much like a VTS) that needs to be informed about the arrival. In Trondheim there is usually a local regatta south of Munkholmen each Thursday during the summer months. It would not be a good idea for a MASS to try and press through the flotilla of these small sailing boats, often with children at the helm. Instead a route north of

Munkholmen might be preferred on such occasions. This and much more of local data needs to be collected and made available in a machine- and human-readable format for the MASS systems and the operators in the ROC.

The IMAT project was briefly mentioned earlier [3]. The main goal of the Integrated Maritime Autonomous Transport (IMAT) project is to define and describe needed infrastructure and organization to conduct safe and effective autonomous transport operations. The IMAT project is elaborating with a Local Information Centre concept. A place where such local information as regattas, ferry timetables and the tracking of kayaks and small fishing boats is collected and made available for ROC and automatic queries.

#### 4.7. Mooring

The MASS is finally reaching its destination. Linesmen or an automatic docking mechanism is ready. Just before the docking there needs to be a check that there is nothing between the ship and the quayside: a small rowing boat that has moored in the wrong place, a kayaker resting his tired arms, a swimmer or some obstruction debris. A manual camera check might have to be done before the “mooring” button is pressed and the Dynamic Positioning (DP) system pushes the MASS sideways the final meters on to the quay. Lines are fast: check; power is attached: check; propulsion is stopped: check, containers are de-lashed: check. Maybe a gangway is automatically lowered for maintenance personal to go onboard. And many, many more things that will be done manually at the start but eventually also will be automated.

### 5. Conclusion

This paper attempts to offer an understandable simple and non-technical concept description of the Maritime Autonomous Surface Ship system with a focus on the human element: where and in which capacity will humans interact with the system, in ports, in the remote operation centre, onboard small crafts and on the bridge of other conventional ships. We have done so by describing a typical voyage of a small electrical container shuttle on a coastal voyage on national waters along the Norwegian coast. Much of what has been said are conceptional thinking by the authors and do not necessarily represent official views from maritime authorities in Norway or internationally, but the authors have for many years worked within the autonomous ship domain and possess some degree of domain knowledge.

We hope that this paper may inspire some engineers working with the technical realisation of this complex system to acknowledge the need for human factor’s engineering, and that the way forward is facilitating a strong teamwork between automation and humans.

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