Can unmanned ships improve navigational safety?

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Abstract

Autonomous vehicles are appearing in ever-more fields such as aviation, public transportation and the automotive sector. That's why it is not unlikely to see the deployment of unmanned merchant ships at some point in time. The collaborative research project MUNIN originates from this idea and aims to develop and verify a respective concept. The ship will primarily be guided by automated on-board decision-making systems but can also be controlled by a remote operator from a Shore Control Centre. The motives behind unmanned and autonomous ships include the shortage of skilled mariners and the facilitation of slow steaming strategies. This shall reduce the use of fuel and thus decrease ship exhaust gas emissions and operating expenses. Another motive, on which this paper will focus on, is the potential to improve navigational safety. So-called "human errors" are claimed to be responsible for the majority of accidents at sea. Thus, substituting the overtired officer of the watch by a nautical officer ashore bears potential to improve the safety of navigation.

Keywords: Autonomous ship; unmanned ship; navigational safety; maritime safety; MUNIN

Résumé

Des véhicules autonomes apparaissent dans de plus en plus de domaines tels que l'aviation, les transports publics et le secteur automobile. C'est la raison pour laquelle il n'est pas improbable de voir le déploiement de navires marchands sans équipage quelque part dans le temps. Le projet de recherche collaborative MUNIN est à l'origine de cette idée et se donne l'objectif de développer et de vérifier ce concept. Le navire est principalement conduit par des systèmes automatiques de prise de décision placés à bord, mais peut aussi être commandé à distance par un opérateur depuis le centre de contrôle à terre. Les motifs en faveur du développement de navires autonomes sans équipage incluent le manque de marins qualifiés et l'aide à la mise en place de stratégies de navigation à vitesse lente. Cette dernière permet de réduire la consommation de carburant et ainsi de diminuer les émissions de gaz d'échappement et les coûts opérationnels. Un autre motif sur lequel l'article insiste, est la possibilité d'augmenter la sécurité de la navigation. Ce qu'il est convenu d'appeler "erreurs humaines" est reconnu comme responsable de la majorité des accidents en mer. Ainsi la substitution de l'officier de quart ultra-fatigué par un officier du contrôle de la navigation installé à terre porte en elle une possible amélioration de la sécurité de la navigation.

Mots-clé: Navire autonome; Navire sans équipage; Sécurité de la navigation; Sécurité maritime; MUNIN

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Nomenclature

ASC	- Autonomous Ship Controller
ASS	- Advanced Sensor System
COLREG	- Conventions on the International Regulations for Preventing Collisions at Sea
DV	- Daylight vision
FSA	- Formal Safety Assessment
IMO	- International Maritime Organization
IR	- Infra-red
MUNIN	- Maritime Unmanned Navigation through Intelligence in Networks
OOW	- Officer of the Watch
UNCLOS	- United Nations Convention on the Law of the Sea
SCC	- Shore Control Centre
SOLAS	- International Convention for the Safety of Live at Sea
STCW	- International Convention on Standards of Training, Certification and Watchkeeping

1. Introduction

Autonomous vehicles are appearing in ever more fields such as aviation, public transportation and the automotive sector. Also in the maritime area, there are a number of autonomous underwater research and military vessels as well as small autonomous surface crafts available and in use. Development and application started with remote underwater vehicles, but up to now small autonomous surface vessels are available and the sizes are increasing. The US Navy Masterplan even contains surface vessels up to 11m length (US Navy 2007). However, currently there are at least doubts about how to include such vessels into the international framework of rules and regulations on the seas (Allen 2012). Thus, a prerequisite for implementing unmanned ships also in the size of freight vessels is a clarification of the current legal framework on how such ships need to be incorporated (Rødseth et al. 2012). Scepticism regarding unmanned vessels exists and thus accepting unmanned vessels requires that those vessels are at least as safe as or even safer than current vessels. For maritime transportation, the absolute number of fatalities due to safety-related accidents is low compared to other modes of transport and this number is even more decreasing. Nevertheless, nearly 4500 seafarer and passengers lost their lives worldwide between 2006 and 2010 (IMO, 2012).

This paper aims to show, how an unmanned vessel and its related technology can even further improve the safety of navigation. Therefore, the MUNIN project, aiming to develop a concept for an unmanned and autonomous merchant ship, will be introduced in section 2, where its rationale and aspired safety benefits are described. Section 3 gives then an overview of current ship operations and outlines current drawbacks that led to human failures and accidents. On this basis, section 4 explains MUNIN's concept of autonomous navigation and how this can contribute towards safer maritime transport. Section 5 will show potentials of certain technology development to enhance safety, even in the absence of unmanned vessels, before the last section gives an outlook and points towards the next challenges.

2. The MUNIN project

Aiming to develop a concept for unmanned and autonomous ship operation, MUNIN is a research project funded by the European Commission's Seventh Framework Programme. While the name is an acronym for *Maritime Unmanned Navigation through Intelligence in Networks*, it also makes reference to a character from old Norse mythology. Munin, meaning *memory* or *mind*, is one of the god Odin's ravens who flies around the world independently during the day and distributes what he has gathered to his master in the evening. Like the raven, the unmanned ship shall travel autonomously around the world, but return safely home to its harbour.

2.1. MUNIN and the European Waterborne Transport Platform

MUNIN covers one of the twelve defined exploitation outcomes of Waterborne TP. This initiative of a cluster of European maritime stakeholders has published a vision paper for the future development of the industry regarding competitiveness and innovation while also considering safety and environmental requirements. Along with a strategic research agenda and an implementation plan it is being used to outline national and European R&D Programmes.

The three pillars on which this strategy is based on are:
- Safe, sustainable and efficient waterborne transport,
- Competitive European waterborne industry and
- Growth in transport volumes and changes in trade patterns (Waterborne TP 2011a).

Based on those principle objectives, a number of exploitation outcomes have been identified to strengthen Europe's maritime sector – among them is the development of an *Autonomous Ship*. This is described as a ship equipped with modular control systems and communication technology to enable wireless monitoring and control, including advanced decision support systems and the capabilities for remote and autonomous operation. In contrast to other outcomes, this vessel shall strengthen all three pillars of the strategy (Waterborne TP 2011b). MUNIN follows a similar definition of an autonomous vessel, as it is a vessel, where no persons are on board for the whole or only parts of the voyage. Thus, the ship, with partial support from remote control, must be able to conduct a deep-sea voyage on its own (Rødseth 2012).

2.2. MUNIN's rationale

The basic motivation to project the development of an unmanned and autonomous ship is to contribute to the aim of a more sustainable maritime transport industry. As a large proportion of worldwide forwarding is carried out by sea it may be considered to be one of the main driving forces of today's global economy.

At present, a fierce competition between shipping companies is putting a lot of economic pressure on all parties involved in maritime transportation. At the same time, international legislation increasingly imposes requirements to reduce ship's ecological impact. This imperative to reduce costs and emissions leads shipping companies to the conclusion that slow steaming must be the solution to their current hardship situation. This has the unfavourable ancillary effect of increasing voyage times, thus creating an even higher demand for seagoing personnel. The factual lack of qualified masters, officers, engineers and even ratings, especially in Europe, has been obscured to a certain degree by the current shipping crisis (BIMCO 2010).

The development towards an unmanned and autonomous ship represents a comprehensive solution to meet those three major challenges of the maritime transport industry:
- Reduce operational expenses,
- Reduce environmental impact and
- Attract seagoing professionals.

Firstly, it will allow reducing personnel costs on board. This will further increase the economic viability of slow steaming ships and contribute to the reduction of operational expenses. Secondly, these extended costs saving potential will further increase the general application of slow steaming. The overall decrease in fuel consumption will consequently result in lower exhaust gas emissions. Thirdly, it will open new professional perspectives for mariners. Instead of being disconnected from home for many months, the concept envisages highly qualified shore-based positions (Rødseth et al. 2012).

2.3. MUNIN's vision

What is aspired by the project consortium is a ship capable of conducting a deep-sea voyage with the assistance of an onshore service provider, the Shore Control Centre (SCC). The tasks of berthing, unberthing and navigating in coastal and congested waters would basically remain unchanged and still be carried out by an on-scene bridge team. But as the ship reaches the open sea in the anticipation of a long ocean passage, the crew will disembark and return to shore, leaving the ship unmanned and operating autonomously. From this point on, it will independently proceed towards its port of destination.

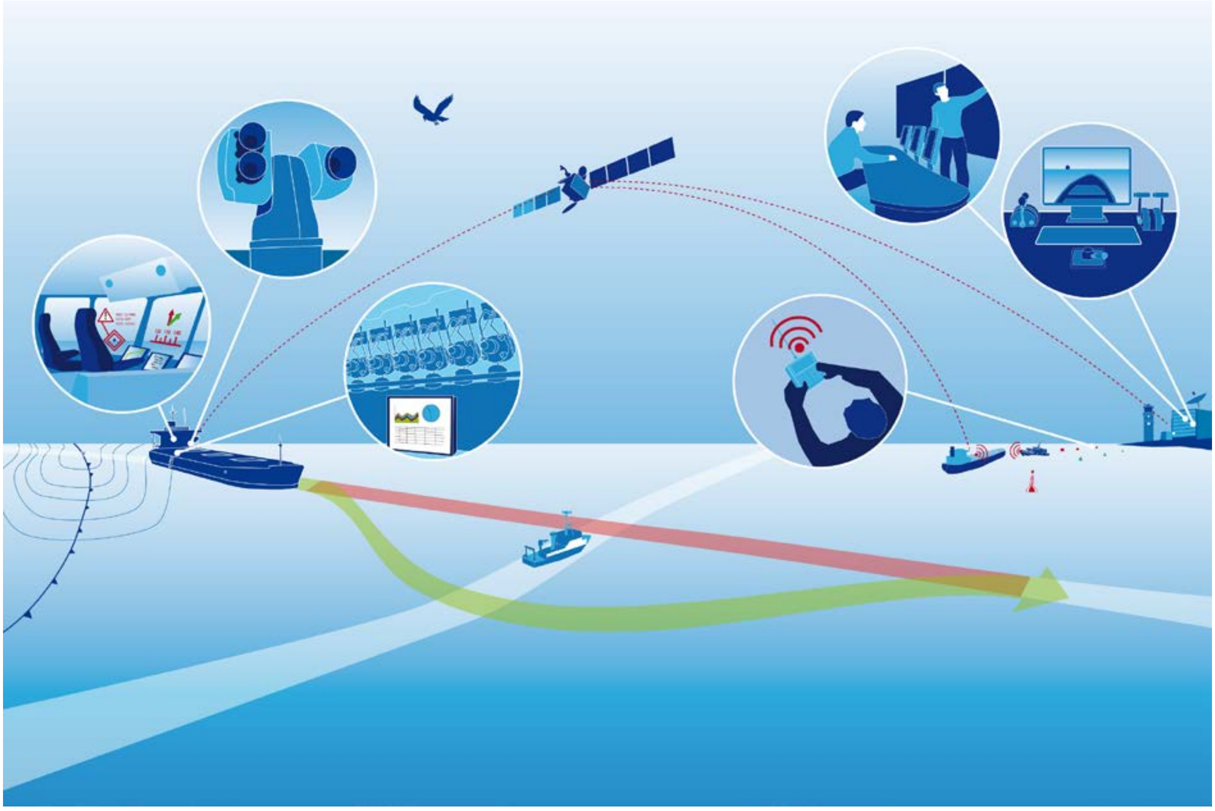

Fig. 1. MUNIN vision picture (Burmeister et al 2013)

An Advanced Sensor System (ASS) will monitor the surrounding of the ship and assure highly accurate object detection, tracking and identification. Through sensor redundancy and the fusion of single readings, the accuracy and reliability of the used values will be much higher compared those of conventional devices. The autonomous navigation of the ship will consist of two central components; one module for collision avoidance and another one for weather routing. If a close quarters situation with another ship should be encountered, the first module will recognize the traffic situation and respond to it according to COLREGs. Should floating objects or fishing nets be discovered, the ship will carry out a respective evasive manoeuvre as well. The second module will constantly assess the prevailing meteorological conditions, monitoring actual data and reviewing forecasts received from stations ashore. In case heavy weather is expected, a deviation track will be calculated and implemented after acknowledgement by the SCC. When the ship is approaching its destination, a conning crew will board again to take over command and guide it into port (see Figure 1).

2.4. MUNIN's possible effects on the safety of navigation

The results of the project will provide a number of short-term advantages for existing ships, e.g. new concepts for maintenance and operation as well as improved applications for navigation. As autonomy depends on highly reliable systems, concepts will be developed to meet this requirement. Fitted on conventional ships these systems will help to reduce the number of technical malfunctions, enable longer maintenance periods and help to prevent major failures leaving a ship disabled and drifting in the open sea.

Large improvements are expected in the field of navigational sensor technology. Basically, approved sensors will be employed in a greater number to assure sufficient redundancy. But unlike today, all gathered data will be thoroughly processed to determine and improve the reliability and accuracy of the final output information. Additionally, a completely new sensor type will be introduced: To compensate for the visual cognition of the watchkeeping officer and the lookout a highly capable surveillance device will be employed to monitor the vicinity of the ship. Fitted with DV and IR cameras along with an additional searchlight mounted on a stabilized platform it is capable to provide images day and night. This precise appliance for automated surveillance will exceed the capabilities of a human lookout, especially during night watches. These enhanced sensor technology will assist watchkeeping officers on conventional ships and help to reduce the number of incidents imposed by human failure.

3. Hazards in current ship navigation

3.1. The navigator in his working environment

The tasks which an OWW has to perform on the ship's bridges of today's merchant fleets vary considerably depending on the sea area which is currently transited. Port stays, pilotage and congested waters can be very stressful and demanding while long sea passages tend to be rather monotonous.

As schedules are tight and manning levels are low, a lot of pressure rests on the shoulders of today's watchkeepers. Integration and interpretation of the ever-growing information input from various navigational sources combined with the human cognition requires the navigator to stay highly attentive throughout his shift. Even though an additional lookout would be quite beneficiary under many circumstances, the watchkeeping officer oftentimes remains to have the sole responsibility on the bridge in many cases. This leads to situations in which dynamically developing traffic conditions in the ship's vicinity are not properly perceived and responded to.

Ocean crossings on the other hand are quite the contrary. Navigation is less demanding as there's only little traffic and few restrictions. Long route legs between waypoints require seldom course changes and thanks to the application of autopilots, the ship is able to advance on its track almost independently. This enables the watchkeeping officer either to recover from busier periods or to occupy himself with administrative tasks. Unfortunately, both of these possibilities result in a low situation awareness.

3.2. The human element in maritime accidents

Several studies report that a large proportion of accidents in maritime transportation systems can be attributed to human error (Sanquist, 1992, Blanding, 1987 and Rothblum, 2000). As numbers range as high as 64% to 96% one obvious, but misleading measure would be to reduce the human influence on ship's control. As human failure is a result of other factors, those must be improved to enhance safety sustainably. Human factors which bear great potential for improvement are:

- Fatigue,
- Inadequate communications,
- Inadequate general technical knowledge,
- Inadequate knowledge of own ship systems,
- Poor design of automation,
- Decisions based on inadequate information,
- Faulty standards, policies or practices and
- Poor maintenance (Rothblum, 2000).

4. Approach towards unmanned and autonomous navigation

The IMO has developed guidelines for assessing the risks relating to maritime safety and for evaluating options for reducing these risks. This Formal Safety Assessment (FSA) is a transparent decision-making tool relevant for proposals with far reaching implications with respect to financial, administrative and legislative efforts.

As the introduction of a concept for an unmanned and autonomous ship will surely be meeting these criteria, a thorough review is necessary to identify those hazards which are affected by the concept. This includes an analysis of existing ones, such as the above mentioned human factors, but also of those kind of hazards which might be introduced by an unmanned and autonomous ship. From the issues in question a number of scenarios shall be derived in which the combination of certain frequencies and consequences determines its risk level. The outcome of such an FSA comprises:

- A list of potential hazards prioritized by risk level and
- A description of their causes and effects (IMO 2002).

In a first step, the scope of the investigation and named problem definitions have to be defined. With regards to MUNIN, the project focuses on a dry bulk carrier of Handymax size with 10MW main engine operating in intercontinental trade. The unmanned voyage is restricted to sail on the open seas outside national waters, but partly in the exclusive economy zone. For a detailed hazard analysis, the operational principles and technical concepts need to be taken into account to identify the corresponding risks related to this concept.

4.1. Operational modes

The concept of an unmanned and autonomous ship has defined a number of different operational modes on-board:

- Autonomous execution,
- Autonomous control,
- Remote control and
- Fail-to-safe (Rødseth et al 2013).

In navigationally demanding waters, e.g. in high-traffic or coastal areas a conning crew will be on-board and in charge of ship command. In this additional manned operation mode the ship is navigated in a fully conventional manner. As soon as the ocean passage commences the crew will disembark and release the ship to autonomous execution mode. This is intended to be the principle mode for deep-sea navigation. Periodically, general status indicators will be submitted to shore to enable safe monitoring. The ship will now proceed on its track according to the voyage plan and monitor its environment. Minor adjustments in speed and/or course due to e.g. restricted visibility or caused by evasive manoeuvres can be executed by the Autonomous Ship Controller (ASC) independently within a predefined frame of freedom in autonomous control mode. As soon as a situation is encountered which the ASC is not capable of dealing with, human assistance is requested from the Shore Control Centre. Now, the ship will switch to remote control mode and be telecommanded by a shore-side human operator. In case of loss of communication the ship will be able to carry out certain pre-programmed fail-to-safe modes to respond to arising situations which potentially threaten the safety of navigation. (Rødseth et al., 2013)

4.2. Process modelling

The introduction of unmanned and autonomous shipping raises fundamental questions on how operational processes should best be structured to ensure the prospective safety of navigation. It is assumed that gradual automation will step by step lead the way from today's conventional shipping to truly autonomous shipping in the future. For this reason, the workflows and processes which are applied in navigation today have been recorded, mapped and adopted to the requirements of the project's general concept layout.

Within the MUNIN concept, the main control function as well as the voyage planning is still performed by humans. However, this is done no longer on-board but ashore in the SCC. In contrast to that the functions "Avoid Collision", "Weather Routing" and "Maintain stability" will be performed by the ASC. This is supported by the automated lookout functions within the Advanced Sensor System (see figure 2). In principle, this system is based on existing and reliable navigational sensors with the radar still being the main source of information, as it is already state-of-the-art to gather further nautical data like wave height and direction or small object detection by radar. However, within MUNIN these readings are fused with modern infrared sensors and cross-checked with other data on-board to measure and enhance the reliability of environment and traffic data. From a hardware perspective, this includes an adequate redundancy concept for the sensor system, which is still under investigation, to ensure that a single technical failure is not degrading the autonomous system's capability to fulfil safety-critical functions so that the ship is constantly operational.

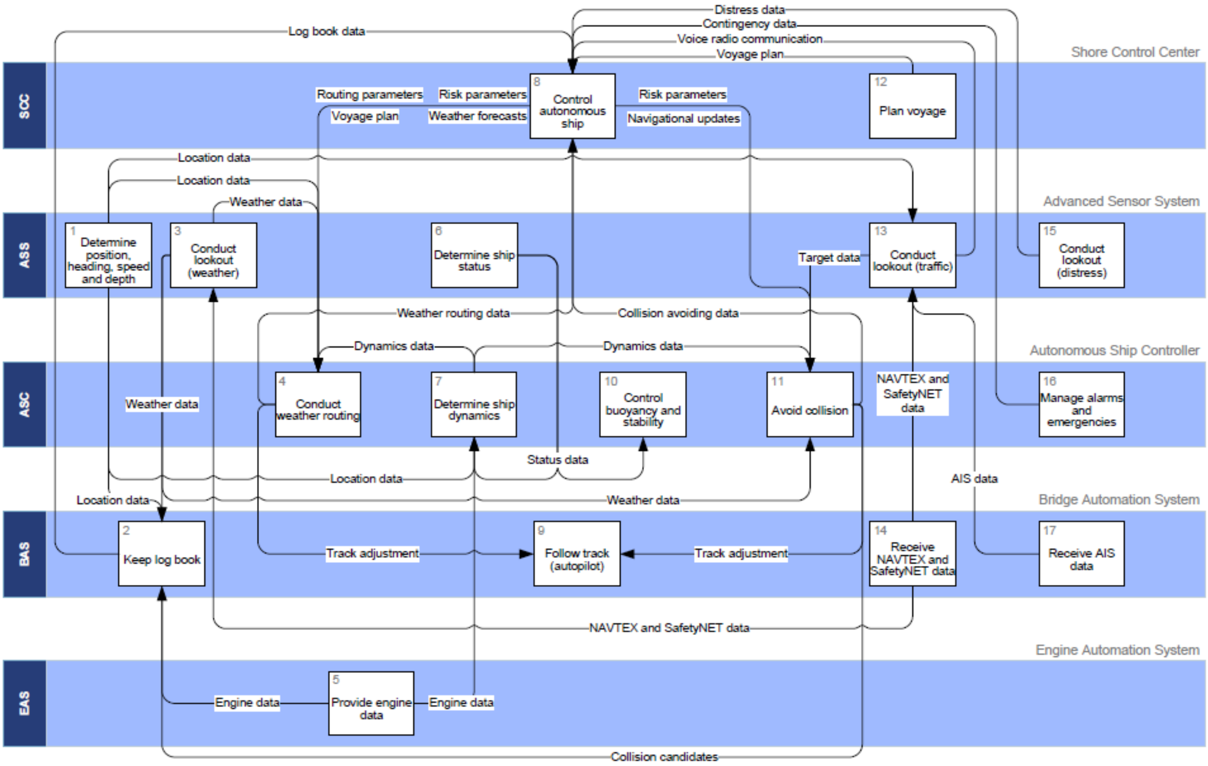

Fig. 2. MUNIN bridge processes (Bruhn et al 2013)

By keeping close to existing operational standards the implementation of individual elements of the project's anticipated outcome shall be eased to smoothen the general technological advancement in shipping. Furthermore, the necessary adoption of international law governing ship operation shall be reduced to a minimum. Based on those legal and liability requirements, imposed mainly by e.g. UNCLOS, SOLAS, STCW and COLREGs, and the corresponding actual workflows and processes, the redesign has been conducted and the process map for autonomous navigation has been developed (see figure 2).

4.3. MUNIN's potential effects on safety and human factors

Recalling Rothblum's list of human factors needing improvement, MUNIN's main contribution regarding safety might be a reduction of fatigue. Instead of overtired mariners on the high seas, automatic systems will take on routine tasks that calls for abilities that the humans are not best suited for, e.g. extended periods of vigilance. It is expected that the ship will be under autonomous control for the large majority of the unmanned voyage, and operators in the SCC will be supported by automation in monitoring the well-being of the vessels. However, in situations that calls for manual handling from shore many of the challenges of today's manned ships remain. Furthermore, even if human error might have been reduced on-board, it has now moved to the programming and remote control room arenas. How to transfer "ship sense" from a remotely located vessel to the comfortable environment of a control center will be a challenge for the project. Proper integration based on human factors knowledge to combat risks of information overload, will be another. For instance, state of the art full mission bridge simulator technology can be used in emergency situations where trained bridge teams will work in an immerged environment almost as on the actual vessel, thus utilizing traditional experience. Of course, remote control centers simultaneously managing many ships in different areas poses the risk of inadequate knowledge of the ship or of inadequate information. Regarding the latter, the integration of the automated look-out besides the already available autopilot could result in a less subjective interpretation, as such system constantly cross-checks its data with other sensors and eliminates human's tendency to rely on single sources. Additionally, it is also expected, that a roll-out of unmanned and autonomous ships will also lead to a further unification or even standardization of bridges and navigational equipment to enable an exchange between different unmanned vessels and different SCCs worldwide (see also Table 1).

4.4. New hazards and challenges

The issues causing the most concern when it comes to unmanned and autonomous shipping are related to the communication architecture and the interaction between ship and shore. Robust communication channels by various and redundant systems must ascertain a maximum availability and accessibility of the ship.

The establishment of a robust information exchange architecture leads to the question of shore-side information management. As the concept envisages one operator to serve a number of ships it will be necessary to facilitate to keep the human in the loop. Otherwise it will be difficult for the SCC operator to grasp a situation which calls for immediate reaction. That's why it is crucial for the ship to forward information about every measure and action it is taking the shore station. The so-called human-out-of-the-loop syndrome caused by a low degree of activation is considered to be a huge issue in the automatic systems (Endsley & Jones, 2012 and Wickens et al., 2013). To prevent this, a routine set-up will assure that the operator spends certain periods of time with every ship to familiarise with the supervised fleet.

Another great challenge is the interaction between unmanned and autonomous ships with conventional ships. All communication calls will therefore be relayed to the SCC from where the human operator will then reply. Also, like any other merchant vessel, it will be obliged to participate in AIS broadcasting. One of the proposals of IMO's current e-Navigation concept (IMO 2013) is a kind of extended AIS in which ships would additionally display their intended routes. This service will be to the greater benefit of ship to ship interaction, especially if an unmanned and autonomous ship is involved (Porathe et al., 2013).

Table 1. Effects of MUNIN on safety (non-exclusive)

Positively affected human elements	New hazards
Reduced fatigue	Communication link breakdowns
Decisions based on verified information	Breakdowns of non-redundant elements
Uniform ship interface	Human-out-of-the-loop
	Interaction with manned vessels

5. Benefits of unmanned and autonomous shipping

It is reasonable to assume that the projected unmanned and autonomous ship will positively affect the safety of navigation. As stated above does the transfer of the human activities ashore contain a considerable potential for the prevention of maritime accidents. Yet, it will not be possible to achieve realisation of a system which is 100% failure-proof. Therefore, the question is whether an unmanned and autonomous system can be designed which is safer than today's manned systems.

5.1. Shipboard sensor technology

Through the development of an Advanced Sensor System extensive lookout capabilities will be provided. Especially the automated surveillance camera shall assure that no object within a three-mile range will pass unnoticed und thus prevent collisions. Furthermore are the issues of e.g. fatigue, attention deficit and situation unawareness exclusive to human operators and can in fact be completely ruled out by autonomous systems. Those navigational sensors, which are conventionally fitted on-board will still be applied. Simply their number will increase to meet a degree of redundancy which is suitable for autonomy. Furthermore, a concept for sensor fusion will be used to monitor, evaluate and process individual sensor readings to produce an improved sensor output. The ASS will provide highly accurate and reliable data for all aspects of navigation. This leads to the conclusion that the information which is available for decision-making will be far more resilient than it is on any merchant ship today.

5.2. Autonomous deep-sea navigation

Transiting open waters, with basically no restrictions for traffic routing and not limited by low water depths, navigation is only constrained by COLREGs, the "rules of the road", and the prevailing meteorological circumstances.

The MUNIN project will develop two tools to enable autonomous handling of both of these navigational factors. This will only become possible through the provision of enhanced sensor data by the ASS. Any object, which might be detected by either radar/ARPA, AIS or surveillance camera will be monitored, tracked and identified. If a danger of collision should arise, a respective evasive manoeuvre will be calculated and conducted. In case of ship to ship interaction, the applicable COLREG-rules will be fully complied with and as soon as the danger of collision has been averted the ship will independently return to its original track. Similarly, the ship will also deal with harsh weather conditions. Proven observational equipment combined with motion sensors will be used to establish a perception of the current environmental conditions. Additional information input will be gained by analysis of forecasts received from shore. If permissible thresholds are expected to be exceed, an alternative track towards the port of call will be calculated to avoid the adverse weather area.

5.3. Shore-side traffic guidance and assistance

The concept for the Shore Control Centre envisages a facility in which a fleet of unmanned and autonomous ships would be operated. One human operator will supervise a number of ships of alike type to facilitate familiarisation. In pre-set intervals every ship will transmit a number of status indicators to inform the SCC about its general conditions. Every deviation from the normal course of action will be indicated to allow the operator to take action at an early stage, if required. Should a situation develop which cannot be solved by the ship itself nor by a minor intervention of the SCC operator, the full ship control will be transferred to a so-called situation room. This is to be set up like a full scale ship's bridge, comparable to ship handling simulators used for training of nautical professionals. From here, remote control will be executed by a specially trained bridge team, consisting of experienced masters and watchkeeping officers.

6. Further development

This paper has demonstrated the potentials of MUNIN's understanding of autonomous vessels and its related technology towards navigational safety. Besides its promising contribution to reduce fatigue and work overload of navigational offices, especially the development of an automatic lookout can make shipping safer and more sustainable. However, as the technology is still under development, it is too early for a final evaluation. A Formal Safety Assessment is required to gain acceptance of the regulation body IMO in the end. MUNIN has started to identify existing and new hazards, but the detailed assessment is still pending and scheduled for the end of the project.

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