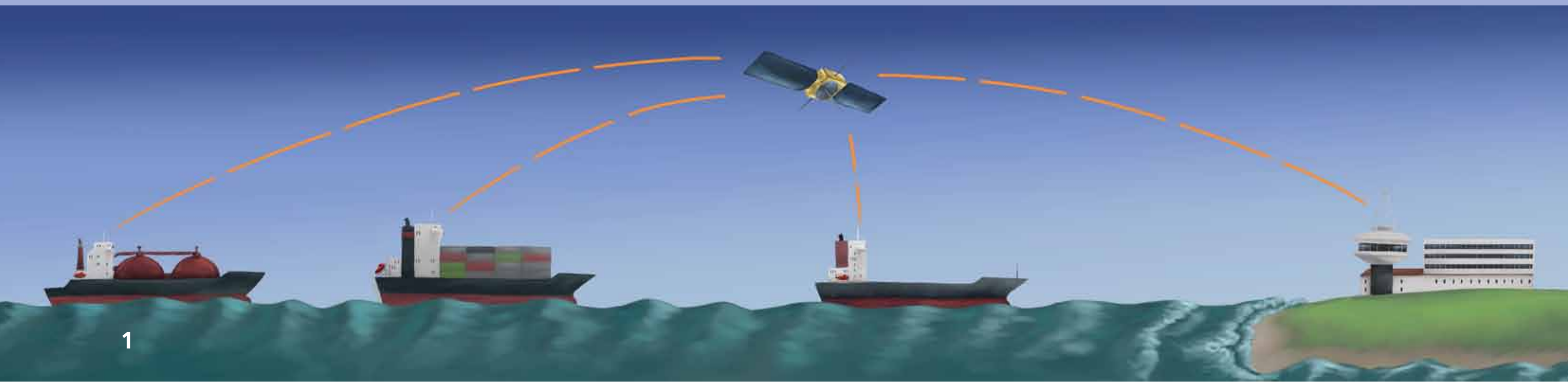
MUNIN

MARITIME UNMANNED NAVIGATION THROUGH INTELLIGENCE IN NETWORKS



RESEARCH IN MARITIME AUTONOMOUS SYSTEMS PROJECT RESULTS AND TECHNOLOGY POTENTIALS

Key facts about MUNIN

Scope:
- Feasibility study
- Test-bed development

Budget:
- Total: EUR 3.8 million
- EU Funding: EUR 2.9 million

The Unmanned Ship web page:
www.unmanned-ship.org

Seventh Framework Programme
Grant Agreement No 314286

European Commission

Project aims and overview

The MUNIN research project has developed a technical concept for the operation of an unmanned merchant ship and assessed its technical, economic and legal feasibility. The concept‘s core is a ship which is completely unmanned at least for parts of the voyage. Furthermore, the project aims for short-term exploitation potentials to support the technological progress in conventional shipping.

The acronym MUNIN is short for *Maritime Unmanned Navigation through Intelligence in Networks*, pointing to the project‘s inherent idea of developing a technology for an unmanned autonomous vessel. Further, in Norse mythology it is also the name of one of Odin’s ravens that each day flys around the world without any guidance, gathering information and in the evening safely returning the information – its „cargo“ – to its master. This also is the vision for the autonomous MUNIN vessel.

The origin of MUNIN lies in the strategic research agenda and the implementation plan of Waterborne TP, a cluster of European maritime stakeholders that has published a vision paper for the future development of the maritime industry regarding competitiveness and innovation while also considering safety and environmental requirements. As one key exploitation outcome for the maritime European research agenda it names the autonomous vessel, *which is 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.*

Unmanned and autonomous vessels can contribute to the aim of a more sustainable European maritime transport industry, as it bears the potential to:
- Reduce operational expenses,
- Reduce environmental impact and
- Attract seagoing professionals.

Case of application

The use case investigated in MUNIN is a dry bulk carrier operating in intercontinental tramp trades. This profile bears a high attractiveness for the MUNIN concept, as additional cargo requirements are low, the attractiveness for slow steaming is high and dry bulk carriers typically transport cargo directly from point to point resulting in a long, uninterrupted deep-sea voyage compared to e.g. container trades. This is an important characteristic, as MUNIN only envisages autonomous operation of an unmanned vessel during deep-sea voyage and not in congested or restricted waters. Those tasks will still be executed by an on-board crew, though the deep-sea/voyage-length ratio is an important economic factor for the operational efficiency.

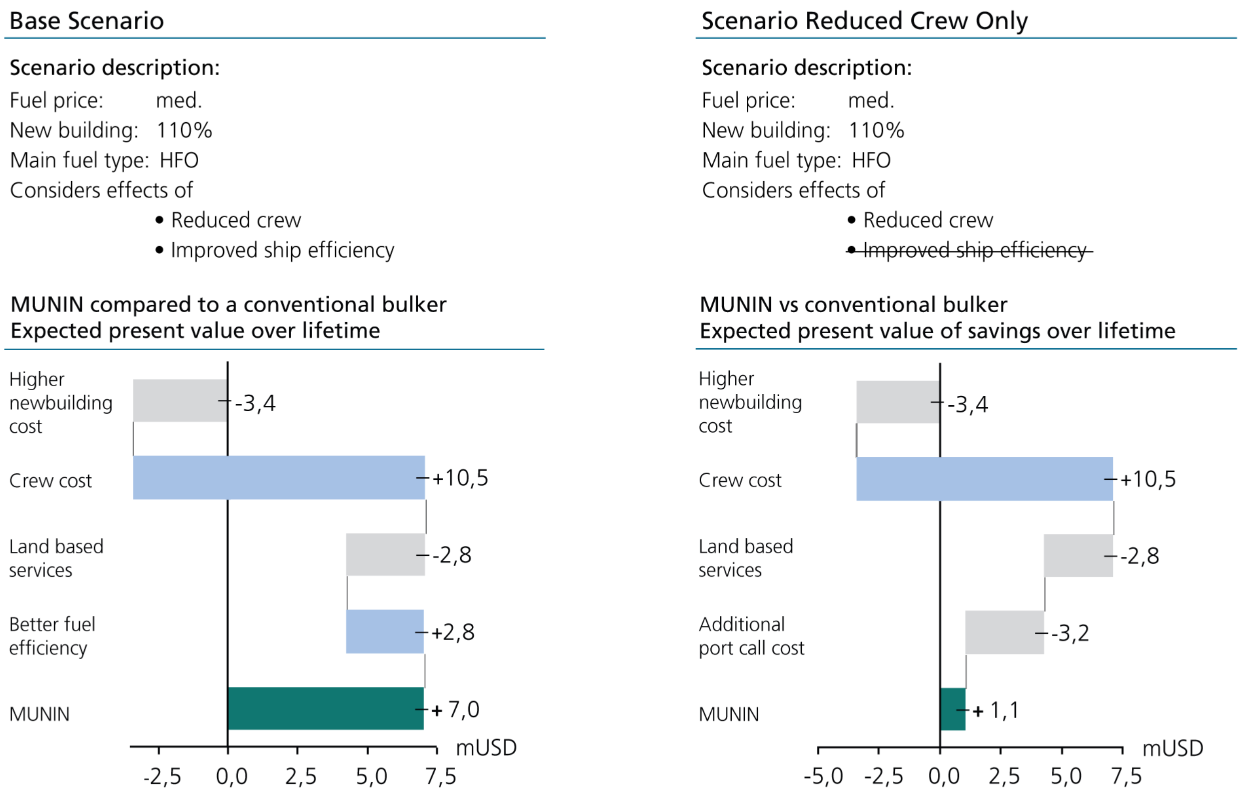
Elements of the concept

Restricted satellite bandwidth in certain regions and high communication costs make a simple remote control solution unattractive. Thus, MUNIN proposes a concept, where the ship is autonomously operated by newly developed systems on board the vessel. Monitoring and controlling functionalities are executed by an operator ashore in the *Shore Control Centre*. Therefore, the MUNIN concept defines the following systems and entities:

- An *Advanced Sensor Module*, which takes care of the lookout duties on board the vessel by continuously fusing sensor data from existing navigational systems, such as radar and AIS, combined with daylight and infrared camera imagery;
- An *Autonomous Navigation System*, which follows a predefined voyage plan within certain degrees of freedom to adjust the route in accordance with legislation and good seamanship autonomously, e.g., due to arising encounter situations or significant changes in weather;
- An *Autonomous Engine and Monitoring Control* system, which enriches the ship's engine room and propulsion automation systems with advanced failure predetection and handling functionalities while keeping the optimal efficiency and taking care of the additionally installed pump-jet acting as a rudder and propulsion redundancy;
- *A Shore Control Centre*, which continuously monitors and controls the autonomously operated vessel after it is being released by the on-board crew of skilled nautical officers and engineers. It comprises amongst others the certain positions:
- A *Shore Control Centre Operator*, who monitors the safe operations of several autonomous ships simultaneously from a cubicle station and controls the vessels by giving high level commands, e.g., updating the voyage plan or the operational envelope of the autonomous system;
- A *Shore Control Centre Engineer*, who assists the operator in case of technical questions and who is in charge of the maintenance plan for the vessels based on a condition-based maintenance system ensuring sufficient reliability of the technical system for the next voyages;
- A *Shore Control Centre Situation Room Team*, that can take over direct remote control of a vessel in certain situations via a shore side replica of the unmanned vessel's bridge including a *Remote Manoeuvring Support System* that ensures an appropriate situation awareness in direct control despite of the physical distance of crew and vessel.

Cost-benefit analysis

Based on a shipping cash-flow model a financial analysis of the developed concept for a new-built MUNIN bulker was conducted. It showed that compared to a conventional manned bulker the autonomous



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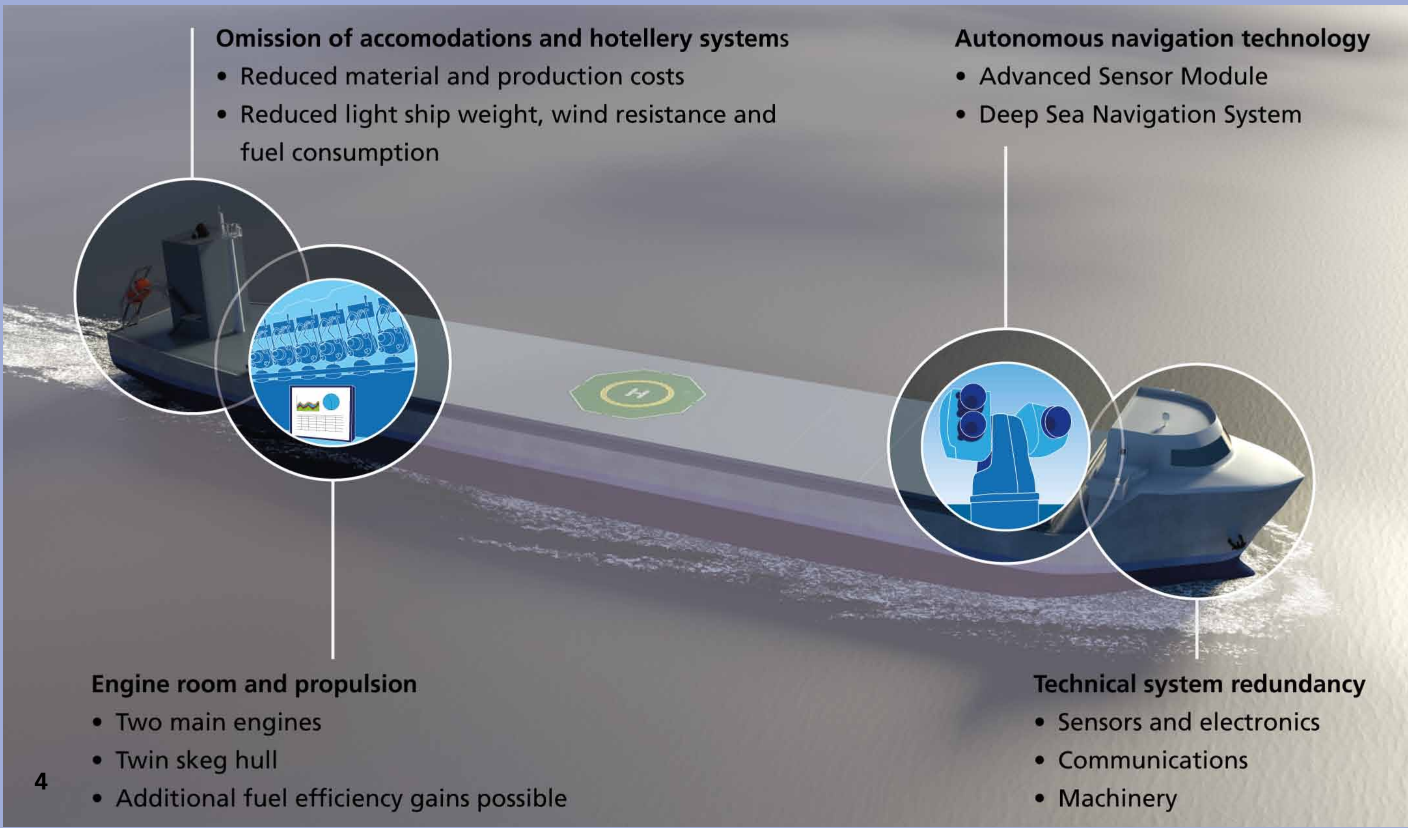
bulker would be commercially viable under certain circumstances. In a base scenario the MUNIN bulker is found to improve the expected present value by mUSD 7 over a 25-year period compared to the reference bulker. Besides cost savings due to a higher efficiency of land-based services in port and the *Shore Control Centre* particularly the fact that the autonomous ship allows for changes in ship design ensures a positive expected present value. Such new innovative autonomous ship designs should make a reduction of fuel consumption and thus emissions possible. However, this is assuming that the depicted challenge of autonomous heavy fuel oil operation can be solved. But even if not, unmanned vessels also bear efficiency potentials in certain niches, like e.g. short sea shipping in emission control areas. While still associated with a high level of uncertainty - due to the early stage of concept development and the limited scope of the project MUNIN – the results indicate that autonomous ships carry the potential to increase the profitability of shipping companies.

Safety and security analysis

Besides profitability, safety is of course levering the implementation of unmanned vessels. The incident categories collision and foundering are responsible for almost 50% of all total losses in the 2005 to 2014 period. Thus it clearly represents the category with the highest incident probability. Furthermore, human errors are a crucial part of the root cause of most maritime accidents. Based on an analysis of collision and foundering scenarios for a MUNIN concept vessel and given a proper operational and robustness testing, a decrease of collision and foundering risk of around ten times compared to manned shipping was found to be possible, mainly due to the elimination of fatigue issues. Also, risks of engine and other system breakdowns are expected to be lower for unmanned ships if proper redundancy is implemented and improved maintenance and monitoring schemes are followed. Fire and explosion represents a relatively small part of all incidents. With the possibility to use more efficient extinguishing systems in fully enclosed spaces, it is likely that the unmanned ship will be much less risk-prone than the manned ship.
Finally, risks from cyber-attacks and pirates are issues that cause concern. However, software systems as well as ships can be designed and built providing a very high resilience against digital and physical attacks. Furthermore, it is unclear whether unmanned and autonomous ships are attractive to such attacks at all.

Legal and liability analysis

Provided that there is reasonable certainty that the unmanned ship can operate at least as safely as a manned ship, in all its functionalities, there is no reason to think that the legal framework cannot be adapted to allow autonomous vessels in maritime transport. The principal areas of concern are navigation and manning. In both cases the unmanned ship will significantly impact the present regulations. Standards in construction, design and equipment of ships will also be concerned. However, overall it can be concluded that the unmanned ship does not pose an unsurmountable obstacle in legal terms. None the less, there will be a high number of issues to be resolved.
In terms of liability, the biggest issue will concern the attribution of the existing ship master duties to the relevant and adequate persons involved in the operation of an unmanned ship. It is unclear whether this legal role should be divided between the SCC operators and masters, or attributed to a single entity in the SCC. Here further research will be necessary.



Autonomous vehicles

The idea of autonomous or „intelligent“ self-steered robots has been around since the advent of computers and arguably even before that. The first modern attempts were on land and later under water, gaining momentum in the 1980s. More recently, the air, sea surface and space have also become arenas for autonomous vehicles. E.g. driverless metro systems are already operating in a number of cities worldwide. However, large unmanned merchant ships have, until the MUNIN project, not been considered a serious possibility. They seemed to be too large and consequences of any mishap too severe to be contemplated.

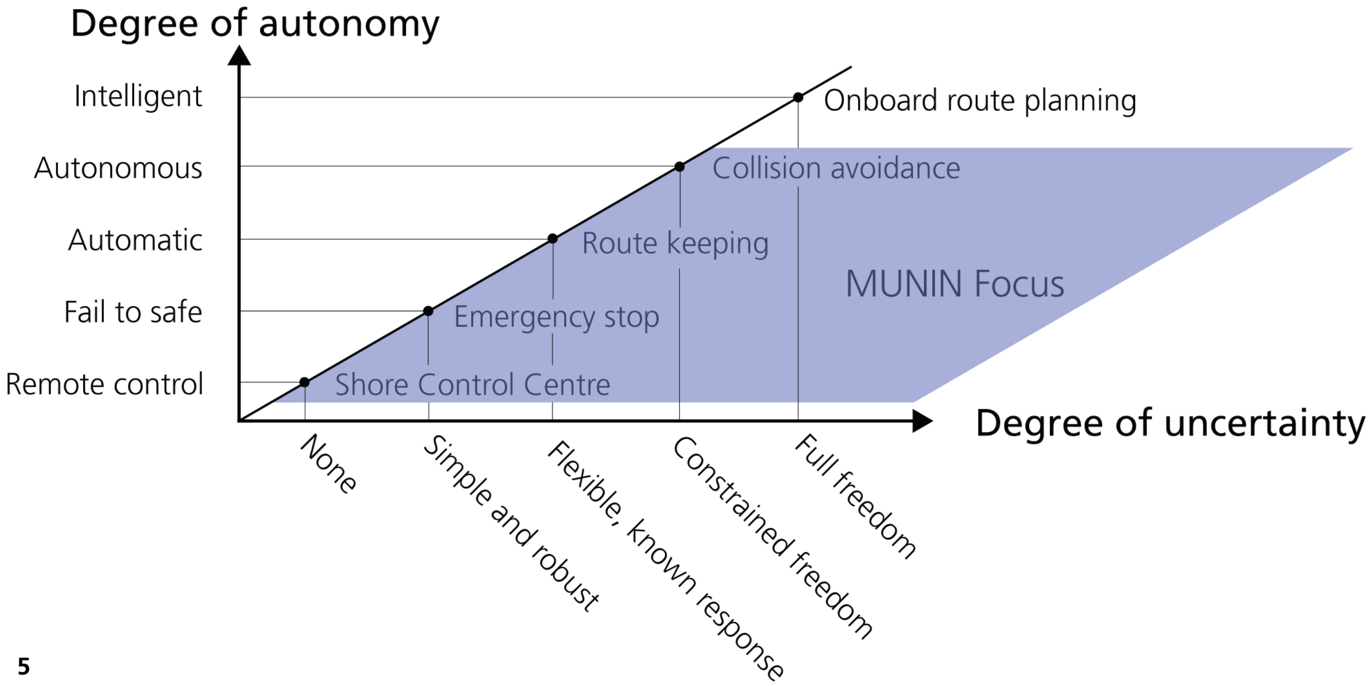
The Waterborne TP strategic research agenda from 2007 listed the autonomous ship as one desirable exploitation outcome, but this was more focused on advanced automation and improved sensors than a fully unmanned ship. Nonetheless, this was the starting point for MUNIN. The project has investigated how a large merchant ship can be operated partially or fully unmanned at the same safety levels than today‘s conventional ships or higher. The use case ship in MUNIN is a handymax dry bulker of about 75.000 dead weight tonnes and a service speed of 16 knots.

Objectives and system components

Unmanned ships are not trivial to develop or deploy as they appear to be contrary to many of the international conventions and regulations which govern the international shipping industry.

There are also several technical components that need to be developed before the unmanned ship can become a reality. The main components of the ship concept investigated in MUNIN are illustrated on the top of this page. Each of the components is given a brief presentation on the following pages. The investigations took place in a number of sub-activities and as project reports are labelled with one of the following activity codes:

- D4: ICT infrastructure, including ship-shore and ship-ship communication, safety, security and reliability of integrated ship data networks. This corresponds to the infrastructure on which the different functions are implemented;
- D5: Bridge functionalities to manoeuvre a ship autonomously require sensor systems, remote manoeuvring, onboard navigation systems and functions in the *Shore Control Centre* for support of the *Remote Manoeuvring Support System* and *Deep Sea Navigation System*;
- D6: Systems and procedures to run the ship‘s propulsion and machinery systems for weeks without physical human intervention for long periods of several weeks. To promote ecological and economical sustainability, high efficiency operation is necessary. This requires an autonomous *Engine Monitoring and Control System* and an *Energy Efficiency System* as well as maintenance functions. It also includes some functions to handle onboard technical problems from the before-mentioned *Shore Control Centre*;
- D7: The continuously manned *Shore Control Centre* with its new types of monitoring and control facilities is necessary to operate unmanned ships autonomously. This also includes procedures on how to interact with other ships, participate in search and rescue operations and with vessel traffic services centres.
- In addition to technical and operational issues, questions regarding legislation, liability, insurance and contractual issues are also investigated within each of the named areas. Additionaly, further project reports have been produced in the following sub-activity areas:
- D8: Proof of concept trials;
- D9: Cost-benefit analysis;
- D10: Alternative autonomous concepts.



Benefits of autonomous shipping

At the outset of MUNIN, one primary aim was to mitigate the higher crew costs for slow steaming. This was the economic rationale for the project. For a typical medium sized bulk carrier, a 30% reduction in speed can save around 50% fuel, even when counting in the extra voyage days. However, increased crew wages would offset much of these savings. Slow steaming also increases the societal challenge of providing attractive working conditions on long and slow intercontinental voyage.
Unmanned ships are also an important contribution to the greening of shipping, e.g. by the use of alternative fuels. For the named reasons, a significant reduction of exhaust gas emissions from shipping is expected. It was also stipulated that an unmanned ship can be operated more efficiently with more advanced automatic energy management systems and improved routing and navigation. A large contribution to increased efficiency would result from the omission of accommodation superstructures.
Today, most accidents and fatalities at sea happen onboard the sailors' own ships. On unmanned ships such incidents will not occur. In addition, human error is a dominant factor in many maritime casualties and automated look-out, navigation and collision avoidance will provide significant safety benefits with regard to that.
These expectations have been confirmed by the project although the economic benefit will depend very much on technical solutions, fuel oil prices and the type of trade the ship is involved in. The unmanned ship will need more reliable and operator-independent technical systems, increasing its costs. This may, e.g. prohibit onboard processing of HFO and require the ship to use more expensive fuel types. Necessary redundancy in machinery and energy production will add to the capital costs. On the other hand, no accommodation section and reduced energy consumption and more efficient propulsion systems reduce both capital and operational costs.

Limitations of autonomous shipping

The main conclusion of the research is that unmanned and autonomous ships can and will be applied where they will be both safer and more cost-effective. Instead of retrofitting existing ships, newbuildings are preferred. As an important result of the project, a list of critical design factors characterizing a viable autonomous and unmanned ship concept has been developed:

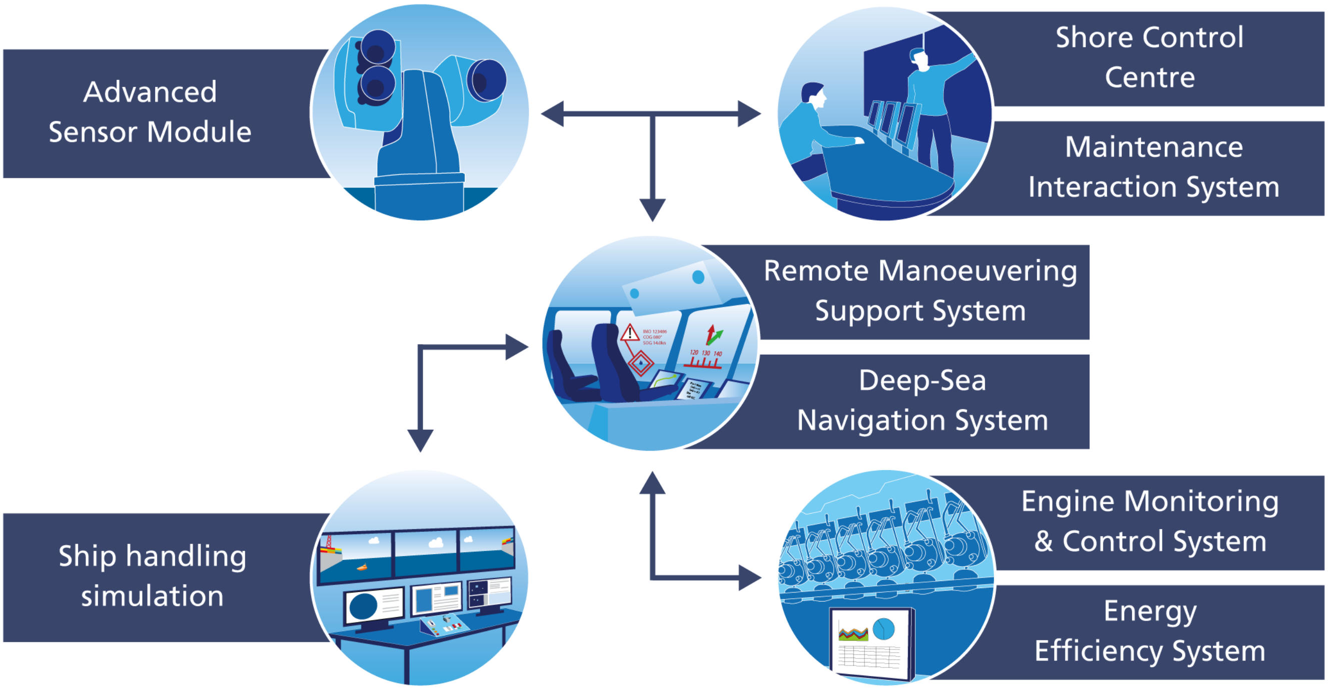
- Shore control: It may be conceivable to build certain types of unmanned ships that are completely independent of a *Shore Control Centre*, but this will require advanced onboard systems and technologies which in most cases are not cost-effective today.
- Operational case: Several factors influence the viability of the concept. The ship will need technical and operational infrastructure at its ports of departure and arrival, making tramp operations less desirable. Transiting dense traffic waters will probably only be possible with direct monitoring functions, affecting the area of operation. In the foreseeable future, operating licenses will depend on agreements between involved flag and coastal states further reducing operational cases.
- New ship design: The unmanned ship will have to be designed from scratch, presumably without superstructure or accommodation section and with simplified and redundant technical systems. This reduces costs and energy consumption as well as the need for onboard maintenance.
- Monitoring and control: Without crew onboard, the systems must monitor technical and cargo conditions, detect failures and unauthorized boarding. Also, appropriate responses must be assured.

Will MUNIN's vision of an unmanned and autonomous ship become reality? And when might that be?

Further research and large scale validation tests in simulation and in-situ environments are necessary to develop applicable solutions for the shipping industry.

Intermediate steps of enhanced ship system automation are expected, allowing for:

- advanced shore-based assistance services through improved connectivity,
- periodically unattended bridges and engine rooms and thus
- more flexible working hours for on-board crews.



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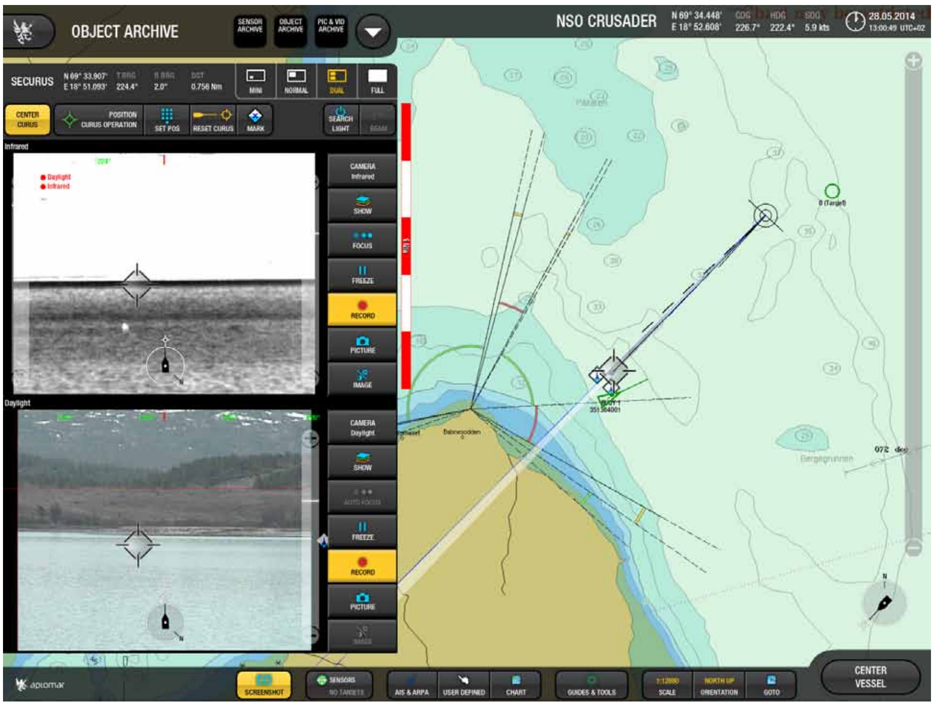
Advanced Sensor Module

On an unmanned ship, sensors and sensor data processing are replacing the perceptions of the officer of the watch and thus are critical elements in the realization of autonomy. The *Advanced Sensor Module* is responsible for object detection and classification and environmental perception. It uses input data from infrared and visual spectrum cameras as well as radar and AIS data to detect objects and determine if they are a danger to the ship or if they need to be investigated further, e.g. to identify life rafts, flotsam or dangers to navigations. It maintains a proper lookout for ship traffic, obstacles and monitors the environmental conditions in the vicinity of the ship. Further, the system collects and assesses data from navigational, meteorological and safety sensors to build a local map of objects and potential hazards. Thus, data from multiple sensors are collected and fused to reduce overall uncertainty and improve the quality and integrity of the so-called world perception model. This overall perception is used as a basis to determine appropriate actions under the prevailing conditions. Sensor information is mainly used by the autonomous *Deep Sea Navigation System* but is also presented on an integrated situation display in the *Shore Control Centre*.



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Deep Sea Navigation System

The *Deep Sea Navigation System* ensures that the ship follows its planned route within the allowable deviations given by the present operational envelope. Deviations can be caused by developing severe weather conditions or to avoid complex traffic situations. The ship's particulars, its technical condition as well as the weather and traffic situation are taken into account. In order to handle a ship on trans-oceanic voyages without on-board crew, the MUNIN project has introduced the *Deep Sea Navigation System* which:

- Determines COLREG-obligations towards other ships and manoeuvres the autonomous ship accordingly to the rules;

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- Optimizes trans-oceanic voyage plans based on meteorological forecasts;
- Operates the ship safely in immediate and harsh weather conditions in accordance with the IMO weather guidance criteria.

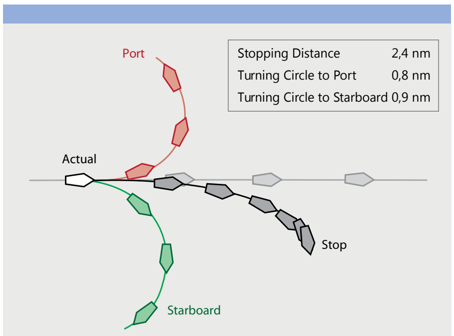
The *Deep Sea Navigation System* can operate fully autonomously but also allows the *Shore Control Centre* operator to interact and thus to remotely control the ship.

Remote Manoeuvring Support System

As an auxilliary for the *Shore Control Centre* and for the *Deep Sea Navigation System*, the *Remote Manoeuvring Support System* has been developed. It aids in carrying out manoeuvres for collision avoidance, while navigating in constrained waterways and in ports. By providing the anticipated ship motion trajectory, it is of essential importance to safe and efficient unmanned and autonomous ship operation. The system provides ship motion predictions resulting from various rudder or engine commands for a specific ship in a its specific environment. Thus, the *Remote Manoeuvring Support System* provides calculations and displays for anticipated ship movements under constraints of manoeuvring ability. This can be done even on a limited capacity communication link and can be used to perform complex manoeuvres by verifying the outcome of a planned set of commands. These motion predictions enable precise autonomous as well as remote navigation.

Engine Monitoring and Control System

The *Engine Monitoring and Control System* is an enhancement to existing ship automation and control systems. The main aim is to add more advanced condition monitoring functionalities. In addition to condition monitoring, adding of increased digital interfaces to the navigation systems and the *Shore Control Centre* are necessary to allow autonomous and unmanned operation of engine room and other technical systems. Continuous monitoring of the critical technical systems is crucial to prevent malfunctions and breakdowns during the deep sea voyage. Monitoring is also important for better maintenance planning. The overall technical and environmental performance of the ship depend on careful diagnostics. Such a monitoring and control diagnostic system for autonomous ship has been developed with robust detection abilities for e.g. broken, burned-on or missing piston rings or for radial wear. This system also detects thermal overloads of the cylinder liner. Remote and effective monitoring and control of the technical systems also requires multi-level aggregation of decision support information. This reduces communication bandwidth and allows tracking of performance trends. The developed concept of technical condition indicators is important in this context. It allows very compact information to be sent to the *Shore Control Centre* with the possibility



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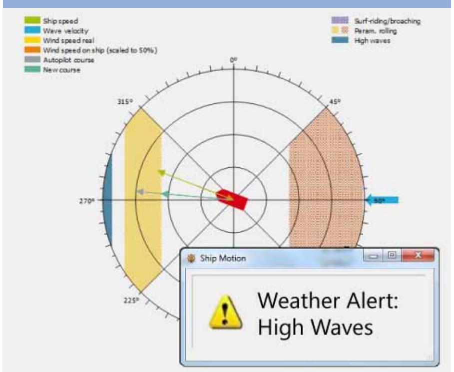

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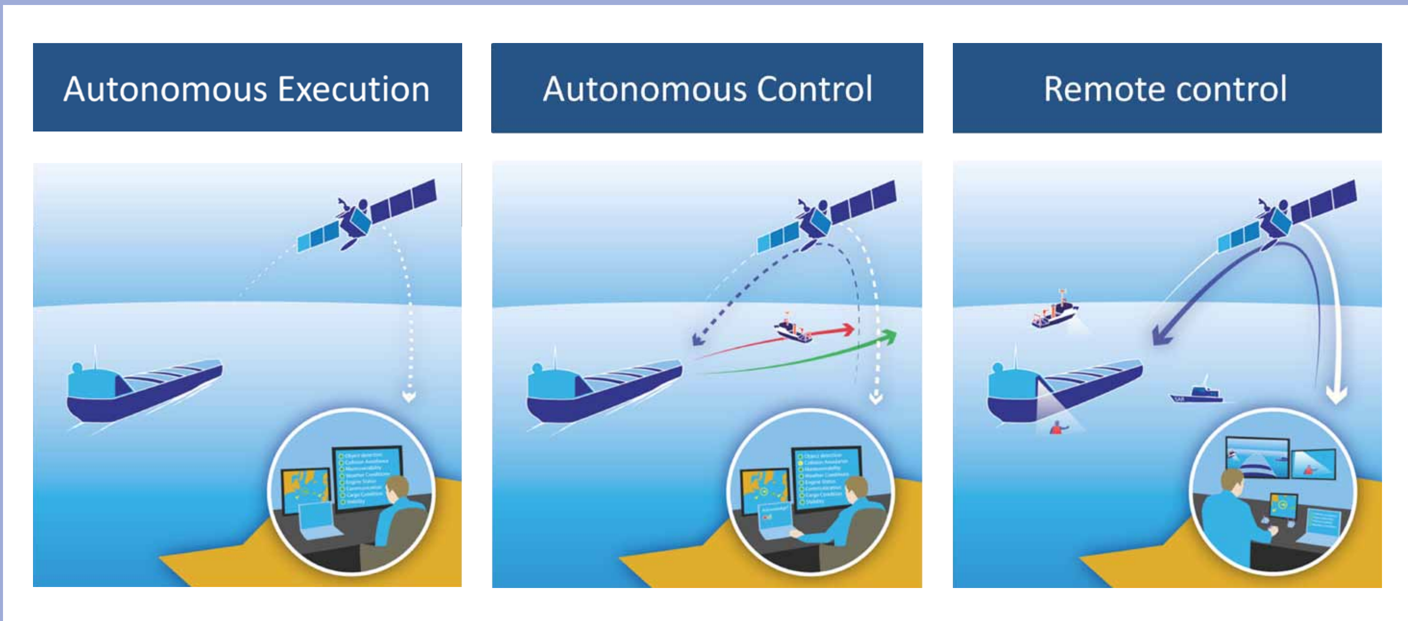
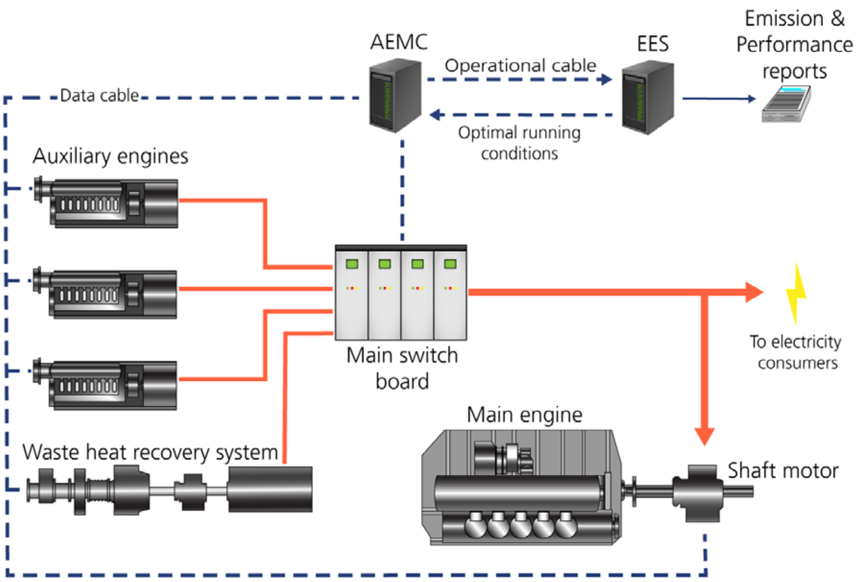


to request lower level measurements or intermediate calculations where needed.

Maintenance Interaction System

Technical operations of an unmanned and autonomous ship are arguably the most complex part of shifting from conventional ships. Today, most onboard systems are designed and built with the availability of crew in mind. Without crew, the systems have to be redesigned or new processes put into place to ensure that the ship will operate without problems when it is at sea and that general ship maintenance can be performed without increasing the risk of ship offhire due to technical failures unnecessarily. The maintenance strategy incorporates a ship system redesign as well as the development of a new maintenance interaction system. The user interface of the system will be integrated in the *Shore Control Centre*, but it will also require new onboard functions. These functions include extended equipment monitoring and condition aggregation functions to minimize satellite communication bandwidth. The project has analysed technical systems onboard existing ships and pointed out those systems needing improved monitoring and support from the *Shore Control Centre*.

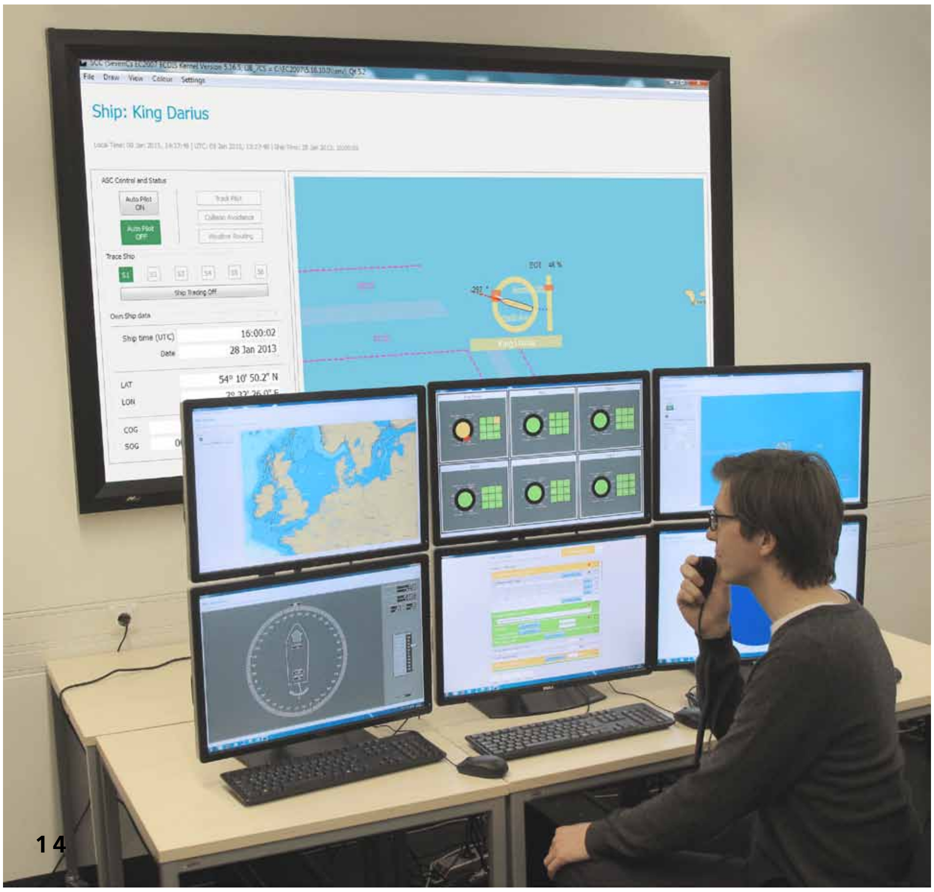


Energy Efficiency System

There are several possibilities for energy efficiency optimisation on an unmanned and autonomous ship. Many also applicable for conventional ships, but the increased degree of instrumentation and automated control symplifies implementation. Also, an unmanned and autonomous ship will have somewhat different engine and propulsion configurations compared to today's ships. One significant difference are the higher redundancy requirements. Duplication of engines, propulsion and steering systems and possibly also diesel-electric systems is necessary. The removal of accommodations and possibly also of heavy fuel treatment systems also allows new types of energy management strategies. MUNIN's *Energy Efficiency System* optimizes the energy management and fuel consumption by analysing the ship's power demands and uses this as a basis for regulating the engine control system. The *Energy Efficiency System* also seeks to use waste heat recovery and other available sources of energy. At the same time it compiles periodic reports on consumption, emissions and the ship performance to the shore operator.

Shore Control Centre

The *Shore Control Centre* acts as a continuously manned supervisory station for monitoring and controlling a fleet of autonomous ships. Most of the time, the ships are operating without any need for intervention from shore. In cases where the automated onboard systems cannot safely handle a situation, assistance will be provided. The limits for what is considered safe are customizable within the so-called operational envelope, setting navigational boundaries. The operational envelope will also include other factors such as visibility, wave height and traffic. From a legal perspective, this supervisory entity is envisioned to take on at least some of the responsibilities of the ships' masters and chief engineers. Further tasks which need to taken over by the shore-based personnel include e.g. VHF communication, VTS reporting, onboard energy management, condition monitoring and maintenance planning. The ship will operate mostly in automatic mode running on track pilot and change to autonomous mode when evasive manoeuvres or routine machinery adjustments need to be made. When the *Shore Control Centre* executes commands, the ship systems will go into remote control mode. In case of emergencies, the ship will activate the fail-to-safe mode if the required shore assistance should not be available due to e.g. a loss of communication. The MUNIN concept relies on the *Shore Control Centre* to handle complex situations as the onboard autonomous controller can only operate inside the defined constraints. This contributes to the balance between technological complexity and economic rationality, making this a viable concept.



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	Chalmers Technical University www.chalmers.se Dr. Scott N. MacKinnon *scottm@chalmers.se*	Human factors Shore control design
	Fraunhofer Center for Maritime Logistics www.cml.fraunhofer.de Mr. Hans-Christoph Burmeister *hans-christoph.burmeister@cml.fraunhofer.de*	*Administrative project coordination* Deep sea navigation Bridge functionality integration Simulation test-bed
	Hochschule Wismar www.hs-wismar.de Dr.-Ing. Karsten Wehner *karsten.wehner@hs-wismar.de*	Remote maneuvering support Engine monitoring and and control
	MarineSoft - benntec Systemtechnik GmbH www.benntec.de/marinesoft Dr. Volker Köhler *volker.koehler@marinesoft.de*	Ship machinery simulations
	MARINTEK, Trondheim www.sintef.no/marintek Mr. Ørnulf Jan Rødseth *ornulfjan.rodseth@marintek.sintef.no*	*Technical project coordination* ICT and communication architecture Maintenance strategies Technical condition indexing
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