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Disclaimer

Executive summary

During the autonomous execution and control mode, the bridge and related operational navigational functions are executed by the autonomous navigation system in place, using data from the advanced sensor module. This concept has been developed in MUNIN Work Package 5 and is briefly described in this document. A section on legal considerations of unmanned navigation as well as initial prototype implementation and test efforts is also included. So far, no absolute conceptual legal or technical barriers have been identified, even though further developments and validation efforts are recommended. Besides its application on an unmanned vessel, the potential to apply the described technology on manned vessels is also mentioned.

List of abbreviations

AEMC	Automated Engine Monitoring and Control
AIS	Automatic Identification System
ANS	Autonomous Navigation System
APT	Aptomar
ASM	Advanced Sensor Module
CDEM	Construction, Design, Equipment and Manning
CML	Fraunhofer CML
COLREG	International Convention on the International Regulations for Preventing Collisions at Sea
ECDIS	Electronic Chart Display and Information System
ERRV	Emergency Rescue and Response Vessel
FRC	Fast Rescue Craft
IBS	Integrated Bridge System
MUNIN	Maritime Unmanned Navigation through Intelligence in Networks
NM	Nautical Miles
NMEA	National Marine Electronics Association
OCT	On-board Control Team
RMSS	Remote Manoeuvre Support System
SCC	Shore Control Centre
SOLAS	International Convention for the Safety of Life at Sea
UAS	Unmanned Autonomous Ship
UCC	University College Cork

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1. Introduction

The overall aim of MUNIN is to conduct a feasibility study, if or if not an unmanned vessel is feasible during deep sea voyage. This is done in different technical, but also in commercial and legal dimensions. One pillar of this research project is the technical feasibilty of an unmanned and autonomous bridge, which is the core of MUNIN's work package 5 (WP5). It is the central component within the MUNIN concept which is responsible for all navigation-related matters. Thereby, navigation can be described as the process or activity of accurately ascertaining one's position and planning and following a route and it is typically performed by the nautical officer on the bridge. Looking into it more in detail, it consists of different sub-activities, i.e. voyage planning, lookout, bridge watch, maneuvering, communication, administration and handling of emergencies, which are already supported by a variety of technical assistance systems on manned vessels today (e.g. Automatic Information System (AIS), Electronic Chart and Information Display System (ECDIS) or Integrated Navigation System (INS)), but are still mainly performed manually /1/.

On unmanned vessels, these activities need to be conducted by autonomous systems to allow for an unmanned operated ship. With regards to the overall architecture of MUNIN, the autonomous navigational functions are conducted by the Autonomous Navigation System (ANS) with the help of the Advanced Sensor Module (ASM). During remote operation, these systems can be enhanced by the shore-based Remote Maneuvering Support System (RMSS).[1]

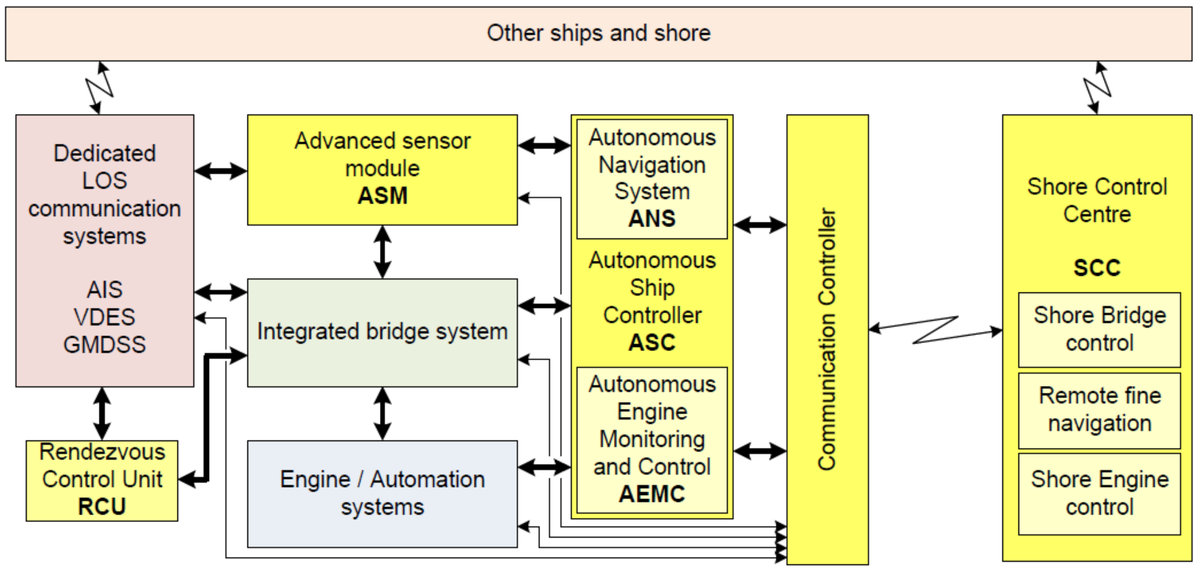

Figure 1: Overview of the high level modules /2/

[1] Even though the RMSS development were originally conducted in WP5, the explanation of results was placed inthe WP7 report, as it better fits there from a readers perspective.

2. Concept overview of the autonomous bridge

Under normal considerations, the unmanned vessel operates in an autonomous execution or autonomous control mode, where no intervention from a human operator is necessary, other than an intial predefined plan has been handed over /3/. In the context of navigation, this means that the Shore Control Center (SCC) or the Onboard Control Team (OCT) have initially set a voyage plan and an operational envelope, but afterwards the operational handling of the vessels should be done by the autonomous systems in place without human intervention /4/.

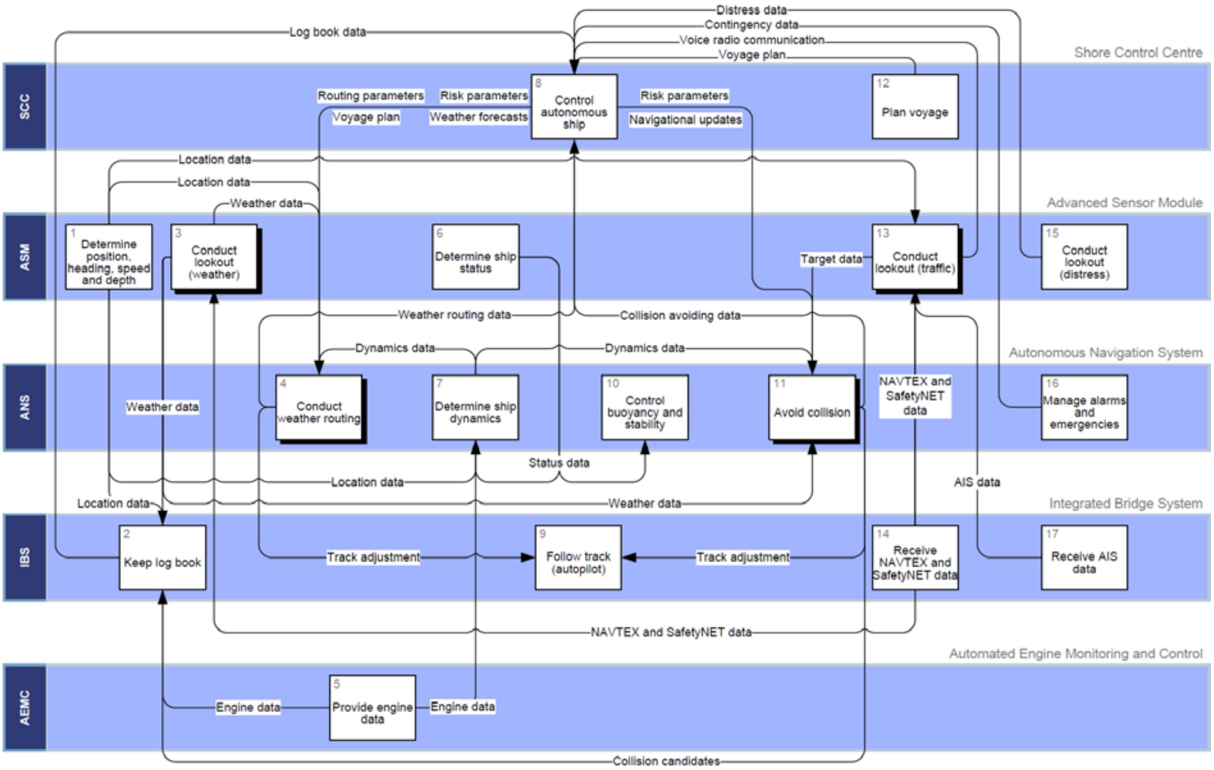

Figure 2: Process Map of the Autonomous Bridge /1/

Within that set-up, relevant input parameters for the process of autonomous navigation are mainly provided by the ASM, which provides the ANS with a perception of the vicinity of the ship, including environmental conditions as well as with target data for detected objects. This is using a sensor fusion-based approach, where raw sensor data from existing navigational sensors are gathered, features are extracted and then correlated among themselves to achieve a robust world model of the vessel's environment /5/.

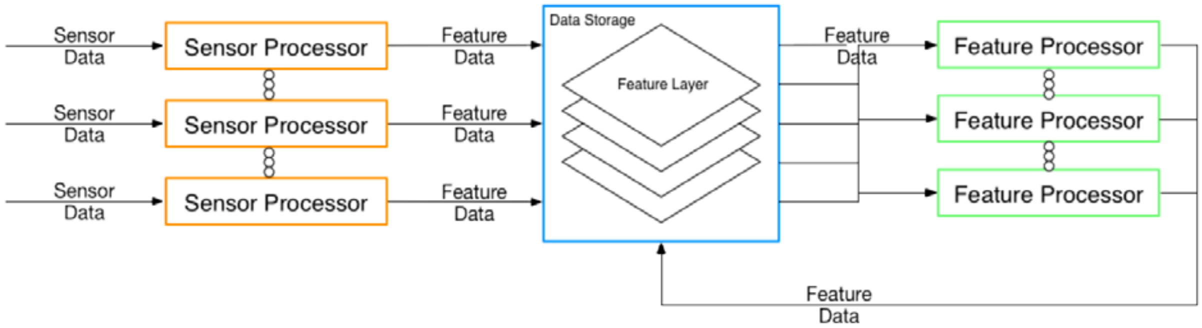

Figure 3: Building a world model in MUNIN /5/

The ANS itself consists of two separate sub-modules which are designed to conduct the two principle tasks of weather routeing and collision avoidance. Furthermore, the ANS is connected to the RMSS and the Automated Engine Monitoring and Control (AEMC) supply data regarding technical limitations of the ship's manoeuvrability under the prevailing circumstances, as well as, to the existing track pilot and engine/rudder control or an existing IBS. Thus, the ANS is normally only adjusting the waypoint list or the voyage plan respectively and is directly steering the vessel in Autonomous Control Mode. However, in certain critical situations, like operations in harsh weather or very close encounter situations, direct commands to engine and rudder control are given to avoid unnecessary delays in resolving critical situations due to track pilot restrictions /7/.

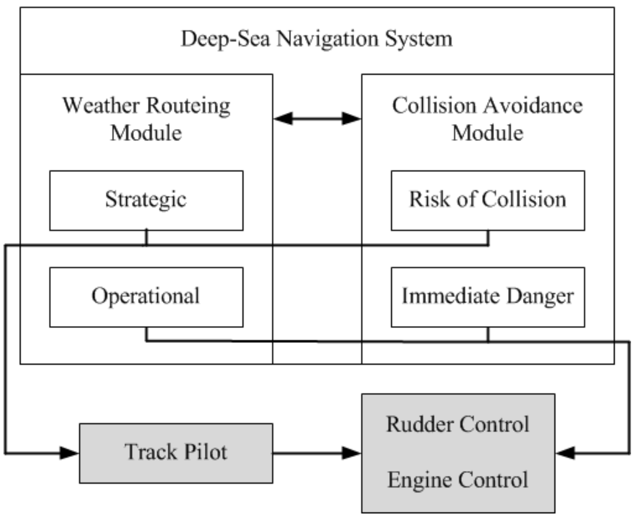

Figure 4: Autonomous navigation system architecture /7/

2.1 Advanced Sensor Module

<table>
<tr><td>Name</td><td>Advanced Sensor Module</td></tr>
<tr><td>Short functional descripion</td><td>Main restrictions</td></tr>
<tr><td>The tasks of the ASM are to maintain an automatic lookout for traffic and obstacles as well as lookout for environmental conditions surrounding the vessel. The goal of the ASM is to maintain lookout by all available means so that an unmanned vessel can comply with COLREG, minimize the risk of collision and ensure safe voyage. However, as existing sensors all have individual limitations, the ASM fuses all individual raw sensor data and then extracts the required information from that data base with the help of sensor and feature processors (so called Sensor Fusion Approach) to build a world model around the vessel /3/.</td><td>COLREG
Physical limitations of sensor technologies like e.g. radar and IR
Data exchange standards (e.g. NMEA)</td></tr>
<tr><td colspan="2">Prototype implementation</td></tr>
<tr><td colspan="2">Within MUNIN, an ASM processor prototype for the sensor fusion concept has been developed based on APT's existing SECurus System, focussing especially on small object detection including corresponding sensor and feature processors. The prototype already integrates marine radar, AIS receiver, general nautical data via NMEA as well as electro-optical sensors like daylight and infrared cameras. It can either be connected to live equipment onboard vessels or run on data recordings in the lab /4/.</td></tr>
<tr><td colspan="2">Module hypothesis</td></tr>
<tr><td colspan="2">The Autonomous Sensor Module can sense sufficient weather and traffic data to ensure navigation and planning function on autonomous vessels and enable situation awareness in an operation room /6/.</td></tr>
</table>

2.2 Autonomous Navigation System

<table>
<tr><td>Name</td><td colspan="2">Autonomous Navigation System</td></tr>
<tr><td colspan="2">Short functional description</td><td>Main restrictions</td></tr>
<tr><td colspan="2">The task of the Autonomous Navigation System is to navigate the UAS safely from boarding point to boarding point. Besides using existing functionalities of Integrated Bridge Systems, it comprises the tasks Conduct weather routeing, Determine Ship dynamics, Control buayancy and stability, Avoid collision and Manage alarm and emergencies /1/.</td><td>COLREG
STCW
IMO MSC</td></tr>
<tr><td colspan="3">Prototype implementation</td></tr>
<tr><td colspan="3">Most crititcal hazards for navigation in deep sea areas are collision and foundering. Thus, the ANS prototype mainly comprises those two functional areas. Safe weather routeing is ensured by anticipatory route optimizationusing the A*-algorithm and emergency handling procedures, while the collision avoidance algorithms works with a formalized description of COLREG. These functionalities, together with a simple autopilot, are programmed in a C++-environment and connected to a ship handling simulator for testing and validation /5/.</td></tr>
<tr><td colspan="3">Module hypothesis</td></tr>
<tr><td colspan="3">A Deep-Sea Navigation System can autonomously navigate a ship safely and efficiently along a predefined voyage plan with respect to weather and traffic conditions /6/.</td></tr>
</table>

3. Legal considerations

So far, autonomous navigation does not specifically appear in the area of maritime law. Thus, the operation of such vessels is considered as operating under the current legal regime, including the Internationa Convention on the International Regulations for Preventing Collisions at Sea (COLREG), the International Convention for the Safety of Life at Sea (SOLAS) or certain Construction, Design, Equipment and Manning standards (CDEM) just to name some of them. Obviously, in some of these areas certain modifications or adaptations will be necessary, either to allow unmanned vessels to comply with their requirements, or to ease their implementation without reducing shipping safety /9/.

One expected clarification with regards to autonomous navigation is undoubtably the question of how to sufficiently comply with COLREG, as an unmanned vessel is also a vessel according to COLREG Rule 3 (a) and thus is obliged to obey it. Critical issues are especially the question, if the ASM is fulfilling Rule 5, meaning that it carries out a proper lookout by sight and hearing and all available means and if the unmanned vessel can sufficiently determine, if it is operating in restricted visibility according to Rule 3(l). Thus, it is a fundamental issue for the unmanned ship to satisfactorily demonstrate that it can perform the same obligations by way of technological equipment, even though formal amendments are probably needed to further specify these obligations for unmanned vessels.

Another issue which would ease autonomous navigation, is the suggestion to consider an amendment to COLREG Part C with regards to AIS-displayed navigational status. Currently, the navigational status according to COLREG is only shown by lights and shapes whose automatic extraction from daylight cameras is quite complex and error-prone. However, this status is also displayed by AIS and this has a much longer range and a better machine-readability than the former. To increase the reliance of an unmanned, but also a manned vessel on AIS-displayed navigational data, it is suggested to consider an amendment giving it the same legal meaning, if AIS is used /2/.

4. Test results

4.1 Advanced Sensor Module

Testing		
Sub-Hypothesis	**Test design**	**Result**
The Autonomous Sensor Module is capable to detect and classify a (<90mtrs) at a range of at least 8 NM, even without AIS data.	In-situ tests on /3/: 1. NSO Crusadar Test with X-Band Furuno FAR 21x7 radar and SECurus System in Norwegian Fjord including small buoy and FRC with a focus on small object detection. 2. Oil-on-Water Exercise Test on several vessels with SECurus System and Furuno FAR 21x7 radar in open waters 3. ERRV test (Stril Herkules) Long range detection test with X-Band JMA-9922-6XA radar only in open waters 4. Oil Rig test (Gullfaks A) Long term test from rig with X-Band Sperry Marine - BridgeMasterE radar focusing on weather and target classification.	Not declined
The Autonomous Sensor Module is capable to detect and classify a small vessel (FRC) at a range of at least 4 NM.		Declined in test, as only 1.15 NM possible
The Autonomous Sensor Module is capable to detect a floating object of standard container size in a range of at least 4.0 NM.		Test not possible due to safety risks, but FRC results can give a prudent indication
The Autonomous Sensor Module is capable to detect a partly submerged object of standard container size in a range of at least 2.0 NM.		
The Autonomous Sensor Module is capable to detect a life raft in a range of at least 3.0 NM.		
The Autonomous Sensor Module is capable to detect a person in water in a range of at least 2.0 NM.		Declined in test, as only 0.53 NM possible with simulated buoy as person in water
The Autonomous Sensor Module is capable to determine if the ship's visibility range is restricted or not.		Not declined, visibility features are detectable
TRL-Status of ASM	TRL 4-5	

Closing remark
It is important to note that the only reason for the negative results was insufficient range. The ASM was able to detect and classify the different objects, but at a shorter range than specified in the subhypothesis. Hence, proving the hypothesis true should be possible, if solutions for the shorter range are identified. Such solutions could be higher accuracy on detection sensors or slower speed on the unmanned vessel. Alternatively, better radar antennas than those used during the test can also further improve test results /3/.

4.2 Autonomous Navigation System

Testing		
Sub-Hypothesis	**Test design**	**Result**
The Autonomous Navigation System Collision Avoidance module can identify the COLREG-obligation of the ship towards all objects in the vicinity in unrestricted waters.	Validation of randomly generated traffic situations and their assessment by nautical experts	Not declined
The Autonomous Navigation System Collision Avoidance module can calculate possible, COLREG-compliant deviation measures for a given traffic situation in unrestricted waters that minimizes the necessary track deviation.	Design of different encounter situations in ship handling simulation and small test vessels and observation of results including nautical expert assessement.	Not declined, but COLREG compliance assessment fuzzy in certain trials
The Autonomous Navigation System Weather Routeing module can optimize the voyage plan based on the ship's hydrodynamics with regard to fuel efficiency for a given weather forecast.	Comparision of calculated track with recorded track from project partner	Not declined, but inconclusive
The Autonomous Navigation System Weather Routeing can maintain the effects of sea state and wind on ship responses (all 6 degrees of freedom) below defined safety levels.	Design of a harsh weather scenario in ship handling simulator with high sea states from different directions	Not declined within test set-up
TRL-Status of ANS	TRL 3-4	
Closing remark		
For more detailed validation of the Collision Avoidance module, large scale analyses are aspired. AIS recorded data might be a possible validation baseline, however certain missing information like the prevailing weather conditions in the specific area make a simple ex-post validation complicated. Furthermore, the decision criteria needs to be further enhanced to make the concept applicable to other vessel types than the choosen bulk carrier in MUNIN and especially the assesment of COLREG-conform collision avoidance in restricted visibility is aspired. In the long run, general accepted operational criterias and/or performance standards for the use of such assistance systems should be developed by additional test campaigns.		

For further assessment of the WR-System, in-situ tests with sea state radar equipment is necessary, as the ship handling simulation test can't cover all relevant harsh weather effects sufficiently. Furthermore, additional recorded tracks must be evaluated to make a more conclusive evaluation with regards to route planning. In the best case, the recorded track is accompained by a decision log of the captain to allow for a better explanation of deviations.

In all cases, a user-friendly integration and a better monitoring possibility of the autonomous systems is wished.

5. Outlook

The results of the work package are mainly on a conceptual and technical level. Additional validation efforts are now needed, to bring this technology into commercial shipping. However, this also requires certain technical advancements and tests of additional sensor technology, to further increase its reliability as an input parameter for autonomous systems. Also, a further enhancement of the system's capabilities for confined and restricted waters might leverage the uptake of these systems – for autonomous as well as for decision support use.

During the development efforts in MUNIN WP5, the fully unmanned bridge has been considered as the final aim. However, it must be concluded that the developed technologies can also provide a baseline for the further development of a class notation 'B0', which could provide safety and efficiency benefits to manned vessels in shortterm due to less legal hurdles. Hereby, B0 means that a reduced bridge crew is only working during daylight hours in flextime, while autonomous technologies take over during night hours /10/.

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