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Risk Assessment for an Unmanned Merchant Ship

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ABSTRACT: The MUNIN project is doing a feasibility study on an unmanned bulk carrier on an intercontinental voyage. To develop the technical and operational concepts, MUNIN has used a risk-based design method, based on the Formal Safety Analysis method which is also recommended by the International Mari-time Organization. Scenario analysis has been used to identify risks and to simplify operational scope. Systematic hazard identification has been used to find critical safety and security risks and how to address these. Technology and operational concept testing is using a hypothesis-based test method, where the hypotheses have been created as a result of the risk assessment. Finally, the cost-benefit assessment will also use results from the risk assessment. This paper describes the risk assessment method, some of the most important results and also describes how the results have been or will be used in the different parts of the project.

1 INTRODUCTION

The MUNIN project[1] is developing a concept for an unmanned dry bulk ship of around 50 000 tons dead weight. The starting point is a conventional bulker with a single engine and propeller and otherwise normal on-board equipment. To prepare this ship for unmanned operation, the concept proposes new sensor systems, new technical operation and maintenance procedures, autonomous navigation functions, a new shore control centre and other components as described in Burmeister et al. (2014b).

As the project is a concept study, no actual trials will take place. However, to show the feasibility of the concept, it has been important to identify the most critical technological, operational and legislative factors that may be obstacles to the concept's realization and to demonstrate that these factors can be managed sufficiently well to make the realization of the MUNIN ship likely. Furthermore, the process of identifying and analysing these factors has to be done in a structured way so that the process and results can be documented and to substantiate the claim that all significant factors have been dealt with.

To achieve these goals, the project has started to develop a risk-based method for design and analysis of “industrial autonomous systems”. An industrial autonomous system is defined as an autonomous vehicle that can operate safely and effectively in a real world environment while doing operations of

[1] The MUNIN (Maritime unmanned ships through intelligence in networks) project has received funding under the European Union’s 7th Framework Programme through the agreement SCP2-GA-2012-314286. See www.unmanned-ship.org.

direct commercial value and which can be manufactured, maintained, deployed, operated and retrieved at an acceptable cost. The corresponding definition of autonomy is an automated system that has the capability of making independent sensor based decisions beyond ordinary closed loop control.

This paper presents some of the results of using the new design and analysis method in the MUNIN project as well as some of the experiences that have been gained through this process.

Chapter 2 gives an overview of some published work on risk based design for autonomous vehicles. Chapter 3 gives a brief overview of the development method and following chapters discuss the main parts of the method: Scenario developments (Ch. 4), system modularization and operational issues (Ch. 5), hazard identification and risk control (Ch. 6), hypothesis formulation and tests (Ch. 7) as well as design verification (Ch. 8). A few comments on the coming cost-benefit analysis can be found in chapter 9. This paper concludes with chapter 10, summarizing the conclusions and experiences made so far in the project.

2 AUTONOMY AND RISK BASED DESIGN

An industrial autonomous system must be a cost effective solution for the intended tasks. "The first question any potential customer is going to ask is: Can the [vehicle] do the job, and if so, at a lower cost?" (Stokey et al. 1999). This certainly applies to industrial autonomous systems, but even for scientific missions this becomes more and more an issue. While science may be more lax relative to cost-effectiveness than commercial industry, they may still have to pay for e.g. insurance or replacement of lost vehicles (Griffiths et al. 2007). However, this is not often a subject of scientific dissertation and papers on risk-based design criteria for autonomous vehicles are still relatively rare.

Some papers are published, mostly in the domain of autonomous underwater vehicles (AUV). One was referenced above (Stokey et al. 1999) and it is an interesting account of what can go wrong with an AUV. The details are not of general interest in the MUNIN scope as application area and operation paradigms are quite different. However, some general observations can be made:

1 Human error is the most common source of problems. This also includes problems with the software design in the control stations.
2 Non-complex hardware errors, such as connectors, battery and calibration of sensors and algorithms, are also a major cause of problems.

There is no reason to believe that this pattern will be much different for other types of vehicles so it confirms the idea that a risk-based design process may be a good choice, but also emphasizes that the risk analysis has to focus as much on "trivial" hazards as on the more complex and intellectually challenging hazards related to the autonomy of the system.

Another paper, (Griffiths et al. 2003) focuses on risk-based design, but still with an AUV as case. It presents a pragmatic approach to safety, focusing partly on problems that are known by experience to have a high probability and partly on simplifying physical designs and programs to keep complexity under control. Some of the main risks identified were:

1 Human error, directly or indirectly, accounts for a high percentage of problems.
2 Relatively trivial physical problems (electronics, GPS receiver, mechanical, power, leaks etc.) also cause a large group of failures.
3 Other significant problems are environmental disturbances (for acoustic transmissions) and software errors.

The paper classifies faults into impact classes and performs a more complete risk assessment, taking consequences of the faults into consideration. While this is of limited use to MUNIN, as the technical domain is very different, it should be quite valuable to other AUV designers. One should also note that statistical models are proposed for some of the fault classes which could be used for more quantitative assessments of expected reliability. Finally, part of the conclusion is that "*This paper has shown that by good design and thorough testing of the 'significant few' systems that could pose high risk to the vehicle, the overall reliability of the autonomous vehicle is not dominated by the complex assemblies needed to provide that autonomy*". This is also encouraging to other autonomous system designs as this has applications not only to AUVs, but can be viewed as a general statement about industrial autonomous systems.

Another fault analysis is done by Podder et al. (2004). This focuses on technical failures and determination of statistical data for quantitative assessment of risk. The observation from this paper is also that most faults are "trivial" in the sense that they do not occur in the more complex sensing, control and decision making software modules of the vehicle.

In (Brito et al. 2010), an operational risk management process model is described. This is partly a quantitative approach where expert judgements are part of the decision making data set. It defines an acceptable risk level and tries to determine if the risks derived from a given mission exceed this level. It is also targeted at operations in high risk environments, i.e. an AUV operating near and under ice, and is not so relevant to MUNIN's operational planning. However, the principles and methods discussed are more quantitative in nature than in the MUNIN project and it will be investigated if variants of the methodology can be used also in the design phase for industrial autonomous systems.

3 THE MUNIN APPROACH

The high-level objectives of the MUNIN design process are:

1 Ensure an acceptable safety and security level for own and other ships and the international shipping community in general.
2 Minimize uncertainty in the missions' intended outcome as well as in unintended side effects.

3 Develop a cost effective system that can compete at a level field in a commercial operational environment.

One key contribution to these three objectives is to keep the system complexity as low as possible. Higher complexity generally means more hidden errors, more development work and higher cost. Higher complexity also implies less deterministic mission outcomes, partly because the autonomous decision making process becomes more complex and partly because unintended system errors may interfere with the process in unexpected ways. To reduce system complexity, we have found that a very effective approach is to simplify the mission and the environmental constraints as much as possible through a careful scenario analysis. This will be returned to in chapter 4.

The risk-based design approach used in MUNIN is based on the Formal Safety Analysis (FSA) method from IMO (2007). The structure of FSA is illustrated in Figure 1. This is the internationally accepted method for doing cost-benefit analysis in the International Maritime Organization's (IMO) rule making process. Thus, it makes sense to use this as baseline as the legislative issues are an important part of the system requirements for unmanned ships. FSA is also emphasizing the identification of cost effective measures to ensure an "optimal" safety level, which is an important objective for MUNIN.

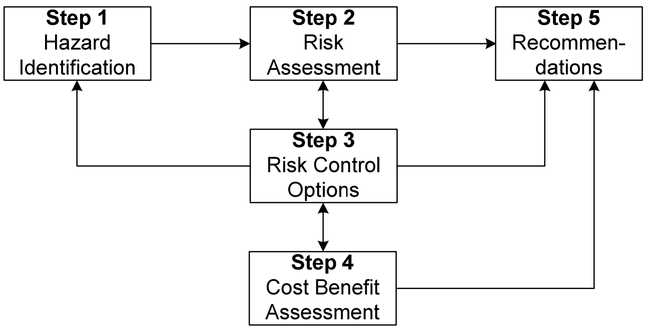

Figure 1. The FSA Process (IMO 2007)

As discussed in (Rødseth & Tjora 2014), MUNIN puts parts of the FSA methodology into a framework as shown in Figure 2. We refer the reader to that paper for a discussion of the background and principles of the method and the framework.

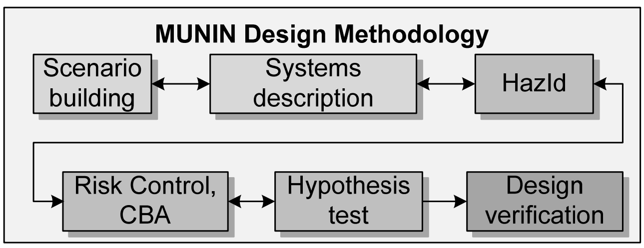

Figure 2. MUNIN Design process

In this paper we discuss some of the results and experiences from the use of the methodology. Each of the following chapters discusses one or two of the steps.

4 SCENARIO BUILDING

The first step undertaken in the analysis of the unmanned ship is to develop a number of operational scenarios in the form of UML (Unified Modelling Language) use cases.

The intention of this exercise is to develop a better understanding of the challenges that an unmanned ship would be exposed to, what support functions it needs and how the operational procedures would have to be implemented to support unmanned operation. This is an iterative process where also a draft physical architecture is developed and the operational principles are laid down. The main scenarios developed are listed in Table 1. They cover normal operation (1 to 8 – unshaded) as well as what was considered to be problems that the system would need to be able to handle (9 to 18 – shaded).

Table 1. MUNIN initial scenarios[2]

1	Open sea mode without malfunctions
2	Small object detection
3	Weather routing
4	Collision detection and deviation
5	Periodic status updates to shore control
6	Periodic updates of navigational data
7	Release vessel from/to autonomous operation
8	Manoeuvring mode - normal
9	Flooding detected
10	GNSS (GPS/GLONASS) malfunction
11	Manoeuvring mode with malfunctions
12	Communication failure
13	On-board system failure and resolution
14	Pilot unavailable: Remote control to safety
15	Piracy, boarding and ship retrieval
16	Rope in propeller
17	Open sea mode with malfunction
18	Unmanned ship in search and rescue (SAR)

By detailing and discussing the scenarios it was possible to identify challenges that could not easily be solved and which could lead to the final system solution not being safe or cost-effective. These challenges were henceforth used to adjust the operational capability of the ship to avoid or limit the impact of the problems. Some typical examples are:

1 Use of a continuously manned shore control center (SCC): This avoids excessive and expensive levels of autonomy while also providing immediate backup in cases where onboard systems fail or are unable to solve problems satisfactorily.
2 Limit unmanned operation to deep sea areas and place crew onboard for port departure and approach: This avoids legal problems in the port and coastal state waters as well as avoiding complex autonomous navigation in heavy traffic areas.
3 Add redundancy in communication systems and add an independent rendezvous control unit: This avoids several critical and high probability single point of failure cases.

2 Detailed UML diagrams are available from http://www.mits-forum.org/munin/index.htm (January 2015).

The scenario building exercise develops the initial system and user requirements as well as identifies critical issues that have significant impact on operational constraints and high level modularization.

5 SYSTEM DESCRIPTIONS

The system description consists of the system modularization and the specification of the operational principles for the unmanned ship.

5.1 *Modularization*

The general system modularization is shown in Figure 3.

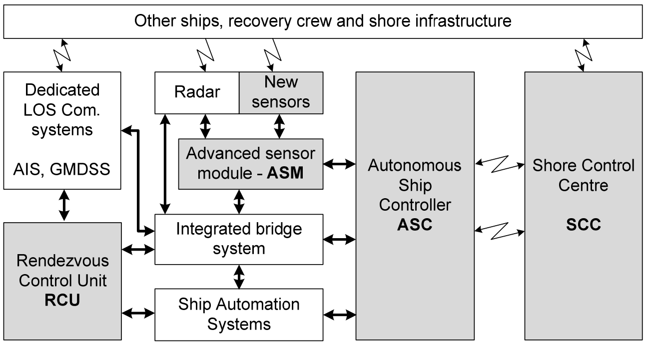

Figure 3. The MUNIN modules (Rødseth et al. 2013)

The new modules and components needed to implement autonomy are shaded. Existing modules are white. The LOS communication block consists of standard systems intended for direct line of sight (LOS) ship to ship or ship to shore communication. This includes the automatic identification system (AIS), global maritime distress and safety systems (GMDSS) as well as a proposed future VHF data exchange service (VDES) as discussed in Rødseth et al. (2013). The radar, integrated bridge and automation systems are other existing ship control systems.

The RCU module is mainly used during port approach and departure when the port operations crew is boarding, but it does also play a special role in recovery of unmanned ships that cannot otherwise be controlled. The RCU is operationally independent from all other autonomous system components and represents part of the fail to safe backup procedures for ship recovery, even when normal satellite communication or autonomous control systems fail.

New sensors consist of a combined CCTV and far infrared (IR) camera that works together with mainly AIS and radar to detect and classify nearby objects. The IR camera is of the Forward Looking IR (FLIR) type. The sensor fusion functions are located in the ASM (Bruhn et al. 2014).

The autonomous ship controller (ASC) consists of various sub-modules for autonomous navigation, engine control, engine condition monitoring and energy efficiency management (Burmeister et al. 2014a, Walter et al. 2014). The shore control center (SCC) is a remote control center with several control stations and functions (Porathe 2014).

Communication between ship and SCC is done over a standard commercial satellite link with a capacity of preferably at least 1500 kilobits per second (kbps), but which will work down to 125 kilobits per second (Rødseth et al. 2013). Another, normally lower capacity satellite link, e.g. Inmarsat or Iridium is used as backup. In addition, the unmanned ship will be able to communicate with other ships through the LOS module.

5.2 *Operational principles*

The operational principles are characterized by a conservative approach to using "intelligent control" in the ship. The inclusion of the SCC removes many complexity increasing factors from the operational scenarios. This means that it is only necessary to implement a relatively limited degree of autonomy in the ship. This also makes it easier to ensure determinism in mission execution. The operational modes are shown in Figure 4.

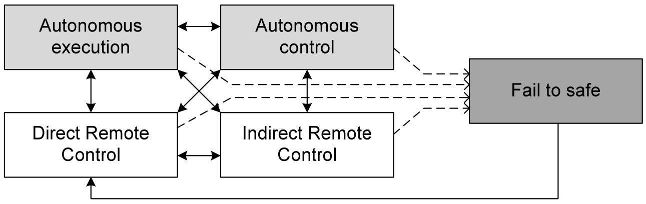

Figure 4. The operational modes (Rødseth et al. 2013)

Autonomous execution corresponds roughly to autopilot operation. It performs navigational and lookout tasks fully automatically as long as more advanced reasoning and decision making is not necessary. This is done without guidance from shore, but with periodic and brief status reports sent to the shore operators. Autonomous control is a mode where the ship, within defined operational limits, performs actions on own initiative to avoid dangerous or unwanted situations. The typical example is avoidance maneuvers when other ships are in the vicinity. Remote control can be direct with continuous and real time control from the SCC or indirect which is when the SCC only outputs high level commands, e.g. waypoints, to the ship without controlling other operational parameters directly. Fail to safe is the state the ship controller will go to when it is unable to continue autonomous operations without SCC assistance and SCC responses are missing or delayed. The specifications of the fail to safe mode are based on pre-programmed instructions from SCC and will normally be updated from the SCC as the voyage proceeds. The specific fail to safe mode will depend on what problem the ship encounters and other environmental or ship parameters (Burmeister et al. 2014b).

5.3 *Operational domain*

The final part of the system description is the definition of the operational domain of the ship. The MUNIN ship is a dry bulk carrier of medium size and the voyage foreseen is iron ore transport between South America and Europe.

During analysis of the use case scenarios, it was also decided to limit the voyage to the deep sea passage and not include transit in congested waters or port approach or departure. There are two main reasons for that:

1 Operation in deep sea areas are mainly under the jurisdiction of the flag state which simplifies the regulatory issues significantly. There is no need to consider different port or costal states' legal regimes.
2 Traffic density and complexity of operation is very much simplified by operating only in deep sea areas. Also, the probability that an error results in a dangerous consequence is lower.

On the other hand, this will also have an impact on cost effectiveness as one needs to have crew onboard for port approach and departure. This means that some accommodation facilities may have to be available. These measures will increase both capital and operational costs and may have an impact on the cost-effectiveness of the whole concept.

6 HAZARD IDENTIFICATION AND RISK CONTROL

The hazard identification was done in a workshop guided by certain semantic components from the MiTS architecture (Rødseth 2011), mainly the ship functional breakdown together with voyage phases and the operational modes.

A total of 65 main hazards were identified. Each of the hazards was then classified according to its consequence if the event should happen and the probability that it will happen. The risk was then graded in three levels: Acceptable (low probability and/or low consequence); Unacceptable (high consequence and/or high frequency); and ALARP: As low as reasonably practicable.

There were several hazards that were classified as unacceptable in the initial ship configuration:

1 Interaction with other ships, whether they follow COLREGS or not, is a critical issue. Navigation and anti-collision software must be thoroughly tested.
2 Errors in detection and classification of small to medium size objects is critical as it may be wreckage, persons, life boats or other objects that need to be reported to authorities. This function must be carefully tested.
3 Failure in object detection, particularly in low visibility, can cause powered collisions. The advanced sensor module must be verified to be able to do all relevant types of object detection, also in adverse weather.
4 Propulsion system breakdown will render the ship unable to move. It is necessary to have a very good condition monitoring and forecasting system to reduce such incidents to an acceptable minimum.
5 Very heavy weather may make it difficult to manoeuvre the ship safely. It is necessary to avoid excessive weather and it is also required to investigate improved methods for remote control if such conditions should be encountered.

The ALARP group of risks represents issues that have to be considered on a cost-benefit basis. One should aim to remove or reduce these risks as long as cost is not prohibitively large.

Among the latter were the various security related hazards, including stowaways, pirate attacks and terrorism. While the scenario of a terrorist using the unmanned ships as a remotely controlled weapon may be seen as a very high risk scenario, investigations into already defined technical barriers showed that it was unlikely that terrorists would be able to take control of the ship as long as communication systems, position sensing and on-board control systems were designed properly (Rødseth et al. 2013).

The identified risk control options associated with the above unacceptable risks are listed in Table 2.

Table 2. Major risk control options

Hzd	Risk control
1	Avoid heavy traffic Object detection and classification Deep sea navigation module SCC and VHF communication with ships
2	Improved maintenance routines Improved condition monitoring Redundancy in propulsion (water jet)
3	Radar and AIS integrated in object detection SCC notification when in doubt
4	Weather routing SCC indirect control
5	FLIR camera and high resolution CCTV SCC notification when in doubt

The risk controls are generally first to try to avoid the dangerous situation, secondly handling it as well as possible on board and thirdly, use the SCC as soon as there is any doubt about outcome. There will also be fail to safe actions for many of these cases that are not listed here.

The defined acceptable safety level is to be at least as good as on normal manned ships, which means that some of the conventional technology can be used to achieve the same safety level. This will as an example apply to the use of radar and AIS in low visibility.

For the propulsion system breakdown, one proposal is to install a water jet that can be driven from the auxiliary generators so that it is independent of all main propulsion components. The idea is to give a type of "limp home" functionality.

The object detection system consists of a number of sensors that should give at least and normally better detection capabilities than a human lookout. Among the sensors is radar, CCTV, forward looking infrared (FLIR) and AIS.

7 HYPOTHESIS FORMULATION AND TESTS

A challenge for designers of autonomous systems is to convince users that the system is safe and that it will do what it is intended to do. Even by demonstrating a certain function, it can be argued that although it worked once, it does not mean that it will work every time. In MUNIN we have decided to address this problem through hypothesis testing.

Oxford dictionary defines a hypothesis as *"a supposition or proposed explanation made on the basis of limited evidence as a starting point for further investigation"*. Thus, MUNIN's main hypothesis for the feasibility test is that unmanned ship systems can autonomously sail on an intercontinental voyage at least as safe and efficient as manned ships. However, a scientific approach requires the hypothesis to be tested to validate it. As MUNIN's main hypothesis W is rather broad, testable sub-hypotheses S_{ij} for each module are derived that are directly dependent on the main hypothesis. Of course, even if all S_{ij} are valid, this does not mean that W holds, but at least a falsification is possible by this approach due to contraposition:

$$(W \rightarrow S_{ij}) \rightarrow (\neg S_{ij} \rightarrow \neg W) \quad (1)$$

The S_{ij} are derived from the identified hazards. Afterwards, appropriate scientific tests can be found and conducted to attempt to falsify the main hypothesis. Thus, the principal test approach of MUNIN is summarized in Figure 5.

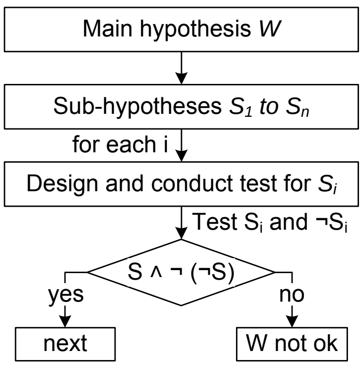

Figure 5. Hypothesis derivation and tests

Table 3. Extract of derived hypothesis (Krüger, ed. 2014)

Number	Hypothesis
W	Unmanned ship systems can autonomously sail on an intercontinental voyage at least as safe and efficient as manned ships.
→ S_1	ASC can autonomously navigate a ship safely and efficiently along a predefined voyage plan with respect to weather and traffic conditions.
→ S_{11}	ASC can identify the COLREG-obligation of the ship towards all objects in the vicinity in unrestricted waters.
→ S_{12}	ASC can calculate possible, COLREG-compliant deviation measures for a given traffic situation in unrestricted waters that minimize the necessary track deviation.
→ S_2	ASM can sense sufficient weather and traffic data to ensure navigation and planning function on autonomous vessels and enable situation awareness in an operation room.
→ S_{21}	ASM is capable to detect a floating object of standard container size in a range of at least 4.0 NM.
→ S_{22}	ASM is capable to detect a life raft in a range of at least 3.0 NM.

While this is not a full proof that W is true, it is a much more convincing argument, particularly if the sub-hypothesis and tests are well designed. However, it is a challenge to design good tests for the negation of S.

As an example, Table 3 gives an overview of a small part of MUNIN's sub-hypothesis with regards to collision avoidance and object detection hazards described in chapter 6.

Based on this hypothesis tree, individual tests are designed and conducted. These tests might differ depending on the concrete circumstances. While e.g. S_{21} and S_{22} can be easily tested by conducting an in-situ-test of the system under different environmental conditions, S_{11} can e.g. be verified by checking the compliance of obligations derived from S_{11} with situations pre-evaluated by nautical experts or court decisions. In contrast, S_{12} can be tested by historical tracks available from AIS-Data providers.

The hypothesis tests will also serve as part of the general software and system testing. However, as the hypotheses normally focus on sub-systems and specific functions, other and more system oriented tests are also necessary. This will be part of the construction and test phase and will not be discussed further here.

8 DESIGN VERIFICATION

For normal ships, the process of getting the required flag state and class certificates is the final design verification. During the certification process, independent third parties examine the technical solutions and issue certificates as proof of safety, security and functionality.

One will need a similar regime for unmanned ships. To be able to sail, the ship must be approved and certified by a flag state and for insurance and for acceptance by the cargo owners as well as other commercial parties, it will also have to have class approval.

One can assume that the approval and certification process for unmanned or reduced manning ships will be similar in structure to that for manned ships. The problem is to define the acceptance criteria and to a lesser degree to test compliance. Another significant problem is that many of the existing international regulations stipulate that there is a crew onboard and that many rules deal with what work processes and what routines are required by this crew to ensure a safe voyage. An obvious example here is the "International Convention on Standards of Training, Certification and Watchkeeping for Seafarers" (STCW) which is obviously not possible to fulfill for an unmanned vessel. This and other codes will have to be reassessed or reformulated to address the use of automated lookouts and helmsmen.

There are already mechanisms in place in the IMO regulatory framework to allow flag state and class to develop new methods for defining requirements to and for testing systems to certain safety goals rather than to technical standards. The concept of "Goal Based Standards" (GBS) was introduced by the IMO Council in 2002. This may be a significant help in adapting at least some of the relevant regulations to unmanned ships. The use of the FSA methodology is an important part of this and is the reason why FSA was selected as baseline for the MUNIN methodology. The use of FSA-based methods already in the concept studies will presumably make it possible to reuse many of the analysis results also in the internationally regulatory processes.

The legal problem is lower when operating only in international waters, where the jurisdiction is almost exclusively that of the flag state. When entering into national waters, the port and coastal states' jurisdiction will come into play as well. This creates a much more complex picture and will in the long term require new international regulations and conventions developed through IMO and possibly other organizations. The MUNIN project has provided some analysis of these issues, but more work is needed to find efficient solutions to the identified problems (Sage-Fuller, ed. 2013a, 2013b).

The hypothesis tests will to some degree also act as verification criteria, although a hypothesis typically only addresses factor from the hazard identification and system modularization individually. Thus, they will not address the system as a whole.

In this context one also has to look at the in-house design verification. This is a normal part of the system development process and is typically undertaken during module tests, integration tests and commissioning of the system. This will be an add-on and a necessary step also to the third party verification related to issuance of certificates.

Design verification will not be done in MUNIN as the project is limited to a concept study. The final test stage in MUNIN will be the hypothesis tests and, following those, the high level cost-benefit analysis. Thus, system verification criteria have not been developed and will not be addressed to any significant extent in this project.

9 COST-BENEFIT ANALYSIS

The cost-benefit analysis (CBA) for the MUNIN concept has not started yet and will be done in the first half of 2015. Also here the results of the risk-based approach are expected to have some impacts.

We expect that the operational simplifications that came out of the scenario analysis will have a positive impact as costs will be reduced when complexity of the technology decreases. The possible exception here is the need for having crew onboard during port approach and departure. Unless this is handled in a way that reduces the need for life support systems onboard, it may offset many of the potential gains in having ships optimized for unmanned operations, e.g. without accommodation areas, less life support systems and using new superstructure concepts.

The risk control options that were identified as necessary in the hazard identification and risk control activities will normally have a negative impact as most risk controls require more advanced software or other technology. However, the structured approach of FSA should guarantee that these risk controls are really necessary and that they give actual benefits to the ship and ship owners.

For the risk controls that were defined as unnecessary or as ALARP, the FSA-based methodology should be expected to optimize the cost-benefits trade off and as such have a positive contribution.

10 CONCLUSIONS

The experiences with the risk-based approach to design have been very good so far. It has defined a necessary and efficient structure to the analysis and design activities and has made it possible to present a consistent and well documented argument for the safety and security of the unmanned ship. It has also given valuable input to the initial cost-benefit work. The project team's impression so far is that the concept of an unmanned ship is viable, although not necessarily as a retro-fit to existing bulk carriers.

The risk based method has in particular been useful in structuring the Hazard Identification process as that is highly critical in defining the main challenges and where development efforts need to be focused. In our opinion, it is not possible to argue for the safety and security of unmanned ships without this type of structured problem analysis.

The early scenario description and analysis exercise has also proven very effective in balancing operational complexity with technical simplifications. This is a critical part of defining the industrial autonomous system's operational scope as a too flexible or too extensive scope can have very high impact on technical complexity and, hence on cost and reliability.

We have not yet used the cost-benefit part of the FSA methodology, but this will be addressed in the remaining half year of the project and reported on later. However, the FSA method has been used in a number of other IMO studies and we do expect that also this part will work well.

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