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Preliminary hazard analysis of a small harbor passenger ferry – results, challenges and further work

To cite this article: Christoph A. Thieme *et al* 2019 *J. Phys.: Conf. Ser.* **1357** 012024

Preliminary hazard analysis of a small harbor passenger ferry – results, challenges and further work

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Abstract. The Norwegian University of Science and Technology (NTNU), is currently designing a small autonomous passenger ferry for up to 12 passengers. The ferry will bridge a harbor channel in Trondheim, Norway. This paper presents the results of the preliminary hazard analysis conducted in the early design phase of the ferry. The main hazards and envisioned risk reduction measures are associated with software failure, failure of communication system, both internal and external, traffic in the channel, especially kayaks, passenger handling, and monitoring, and weather conditions. In addition, this paper summarizes practical challenges encountered in the ferry project. These challenges are related to available hazard and risk analysis methods and data, determining and establishing an equivalent safety level, and some of the prescriptive regulations currently in use by the Norwegian Maritime Authority. The presented analysis and identified challenges may assist other, similar projects designing and developing autonomous vessels.

1. Introduction

The Norwegian University of Science and Technology (NTNU) is currently designing a small autonomous passenger ferry with a maximum of 12 passengers, for crossing a harbor channel in Trondheim, Norway [1]. The ferry is designed with a high degree of autonomy, enabling it to execute the necessary navigational tasks autonomously. A supervisor will monitor the ferry from a land-based control center and may take corrective actions and communicate with the passengers and other vessels.

The ferry will be operating on demand but needs to follow the national regulations for route-going passenger vessels. The regulations by the Norwegian Maritime Authority (NMA) include conducting risk analysis for approval of the ferry and for commencing operation of the vessel [2]. No autonomous ferries are in operation in Norway yet. Hence, there is limited guidance and experience available on how to assess such a project from a risk point of view.

This article presents the results of the preliminary hazard analysis (PHA) of the autonomous passenger ferry to be operated in the Trondheim harbor channel. The analysis was conducted through two workshops gathering different fields of expertise. The identified hazards were evaluated semi-quantitatively. The evaluation gives input to the ranking of the hazards and accordingly their impact on the system design through necessary risk reduction measures; some of these are presented in this article. In addition, this article discusses the initial challenges that are faced by the autonomous ferry project with respect to the assessment, approval process and the Norwegian regulations.

IOP Conf. Series: Journal of Physics: Conf. Series **1357** (2019) 012024 doi:10.1088/1742-6596/1357/1/012024

This article thus gives overall guidance on how to conduct hazard and risk analysis for autonomous vessels and how this information may be used further in the design process. Further work for the ferry project includes a detailed risk analysis of non-conventional solutions, and of scenarios with a high-risk potential.

2. Background

2.1. Hazard and risk analysis

"A hazard is a source of potential harm" [3], and this can be a source of risk. Harm may include ill-health, injuries, death, damage to property, operational downtime, liabilities, damage to the environment, or loss of reputation. A hazard may be, e.g., another vessel traveling through the channel. This is a normal situation and hazards may be regarded as normal and present at all times. When the hazard's potential to cause harm is realized, this is called the hazardous event. For the hazard mentioned above, the hazardous event would be a collision between the ferry and the other vessel. Hazardous events in contrast to hazards themselves are thus abnormal.

Risk is often expressed as the consequences of a (hazardous) event and the associated likelihood of the occurrence. The likelihood is often expressed as probability or frequency [3]. Risk analysis methods models currently used for conventional ships are not necessarily well suited to reflect the particularities of autonomous ships, especially factors related to software, reliable communication, different modes of operation (e.g., autonomous, autopiloted, remote, or manual) [4]. Hazard and risk analysis of autonomous ships has been only addressed on a conceptual level, e.g., the MUNIN project {Rødseth, 2015 #918}, Wróbel et al. [5-7], Ramos et al. [8, 9], or Valdez Banda et al. [10, 11].

The analysis presented in this article identifies hazards, hazardous events, and suitable risk mitigation measures. The analysis was conducted in two workshops with participants having experiences and backgrounds in different domains, such as ship navigation, control theory, risk analysis, design of human-machine interfaces, communication systems and electronics, and vessel design.

The PHA was conducted following four steps: Firstly, define the objective, determine PHA prerequisites, and establish a team. Secondly, identify hazards and hazardous events, which is guided through checklists. Thirdly, estimate frequencies or probabilities and consequences of the identified events. For frequencies and consequences, specially adapted categories are used. Lastly, evaluate and rank risks and decide follow-up actions. Steps 2 – 4 should be iterated through the design progress of a system. The PHA in this paper focuses on natural, operational, human, technical, and malicious events. The categories used for the semi-quantitative assessment are presented in Table 1 and Table 2, for the frequency and consequences, respectively. The design lifetime of the ferry is considered to be 10 years.

Table 1 Frequency categories applied in the PHA workshops. Abbreviation: FI - Frequency Index

FI	**Frequency**	**Frequency (per ship year)**	**Description**
1	Remote	<0.01	The event is likely not to occur in the lifetime of the ferry.
2	Unlikely	0.01– 0.1	The event may occur once in the lifetime of the ferry.
3	Expected	1 – 0.1	The event may occur several times in the lifetime of the ferry (10 years).
4	Frequent	> 1	The event is likely to occur several times per year.

Table 2 Consequence categories applied in the PHA workshops.

Index	Category	Human safety	Economic damage	Environment
0	None	No injuries.	No damage to equipment or other property.	No damage to the environment.
1	Minor	Single and/or minor injuries.	Local equipment damage or small damage to other property. Or, Minor loss of income.	Minor local pollution of the environment.
2	Significant	Multiple minor injuries and/or severe injury.	Damage to ship or to other property. Or, Significant loss of income.	Significant pollution of the canal.
3	Severe	Single fatality and/or multiple severe injuries.	Severe damage to the ship or other properties. Or, Loss of income equivalent to several days of operation.	Severe pollution of the canal.
4	Catastrophic	Multiple fatalities and severe injuries.	Loss of ship or other properties.	Severe pollution of the canal and fjord.

2.2. Norwegian regulations for small ferries and autonomous vessels

A preliminary adoption of the MSC.1/Circ. 1455 [12] has been drafted by the Norwegian Maritime Authority (NMA) describing documentation requirements for the design, construction, and operation of ships with a certain degree of autonomy [2]. The passenger ferry needs to comply with the requirements for a regular route-going ferry with a maximum of 12 passengers or less, due to the planned operational pattern.

Several other regulations need to be considered while designing and operating a small ferry. These regulations shall ensure safe design, passenger safety, environmental safety and safe operation with respect to other vessels. For passenger ships, a risk management system needs to be established. If 100 or fewer passengers are transported in a voyage in Norwegian waters, regulation 2016-12-16-1770 “Safety management for small cargo ships, passenger ships and fishing vessels, etc.” [13] apply. Generally, SOLAS [14] requirements have to be met by the ferry with respect to design and safety features. Additional safety measures for Norwegian passenger ships are prescribed in 1987-06-15-507 “Safety measures, etc. on passenger ships, cargo ships, and barges” [15].

Construction of vessels is regulated in 2014-07-01-1072 “Construction of ships” [16] and in 2000-03-28-305 “Surveys, construction and equipment of passenger ships engaged on domestic voyages” [17]. Several references that apply to the ferry project, regarding specifications for hull design, etc., are made to the Nordic Boat Standard (1990, [18]). Lifesaving appliances need to be available on board the ferry (Regulations 2014-07-01-1019 “Life-saving appliances on ships” [19], and 2009-11-24-1400 “Operation of vessels carrying 12 passengers or less, etc.” [20]). Pollution of the sea needs to be avoided (MARPOL [21], regulation 2012-05-30-488 “Environmental safety for ships and mobile offshore units” [22] and regulation 2004-06-01-931 “Pollution Regulations (excerpts)” [23]).

Different rules prescribe functions and positions be carried out by human seafarers. Certification and qualification requirements are laid out in regulations 2014-12-22-1893 “Supervision and certificates for Norwegian ships and mobile offshore units” [24], 2009-06-18-666 “Manning of Norwegian ships” [25], and 1999-04-27-537 “Watchkeeping on passenger ships and cargo ships” [26]. In addition, existing regulations prescribe the use of navigational equipment and methods (Regulations 2011-12-22-1523 “Qualifications and certificates for seafarers” [27]¸ and 2014-09-05-1157 “Navigation and navigational aids for ships and mobile offshore units”[28]). Other equipment requirements are stated in the regulations 2016-08-30-1042 Marine equipment [29].

These regulations and the requirements therein need to be fulfilled. Otherwise, the shipowner or operator need to document that a chosen solution is equivalently safe as the current standard. Generally, deviations from standard design solutions and components need to be clarified with and approved by the Norwegian Maritime Authority.

DNV GL published rules and guidelines that are relevant for autonomous ships and may assist in the effort to demonstrate compliance. These are the class guidelines for autonomous and remotely operated ships (DNVGL-CG-0264 [30]) and the recommended practice on cybersecurity resilience management (DNVGL-RP-0496 [31]).

3. Results

3.1. NTNU's autonomous ferry concept and context

The detailed design of the autonomous ferry is currently being developed with input from the results of the assessment presented below. The ferry is designed with autonomous capabilities for navigation and docking, passenger registration, charging while on the quay, etc. Autonomy is a system's capability to make choices independent of an external operator or system in order to achieve a mission goal [32].

During the first year, a supervisor will be present on or nearby the ferry, to be able to take corrective measures as fast as possible in case something should not work as expected. Eventually, this supervisor will be relocated to an onshore control center equipped with the necessary interfaces. The ferry will be equipped with an electric propulsion system, with a maximum and normal cruising speed of five knots and three knots, respectively. Several phases of operation are considered in the hazard analysis, including docking, boarding, off-docking, voyage, off-hours (during bad weather or at night), manual/ remote operation, and emergency handling.

The ferry will be crossing the Trondheim harbor channel from Ravnkloa, as shown in Figure 1. The area is busiest in summer, with leisure boats crossing the area and tourist boats leaving from Ravnkloa. A traffic data analysis is pending. The channel is approximately 90 m wide with a depth ranging between 3 m and 6 m. The environmental conditions to be expected during normal conditions are 3.2 m tidal range, 1.5 m/s maximum current speed, 0.5 m maximum wave height, and 10 m/s maximum wind speed. During storms, these parameters may be exceeded. However, the ferry will be not operated during storms and harsh weather.

Figure 1 Area of operation of the autonomous ferry, adapted from [33].

3.2. Hazard and risk analysis

The two workshops resulted in several hazardous events identified and analyzed with respect to their assumed frequencies and expected consequences. For this assessment, the categories in Table 1 and Table 2 were used, and the principle of credible worst-case scenario was applied to assess the consequences before any risk reduction measures are implemented.

The analysis identified the most critical hazardous events to be related to the control system, communication between software and hardware components, the interaction between the ferry and recreational users of the channel and hacking and cyber sabotage. Table 3 through Table 7 summarize the most important hazards, the assumed credible worst-case consequences and the suggested risk reduction measures. The tables do not include all hazards and events that were identified, such a detailed analysis would exceed the scope of this paper.

Table 3 Summary of the most critical hazardous events and risk reduction measures related to traffic in the channel.

Hazardous event	**Consequence**	**Risk reduction measures**
Kayaks or swimmers are close to the ferry.	The ferry runs over swimmers or kayaks or pushes them towards the quay wall.	Test the traffic detection system for kayaks and swimmers. Appropriate visibility, lanterns, and signs on the ferry and in the operational area.
The ferry is overlooked or not recognized by other boats and ships in the harbor channel.	A collision of the ferry with a leisure boat may lead to damage and injuries of the passengers and other traffic participants.	Appropriate visibility, lanterns, and signs on the ferry and in the operational area. Follow the navigational rules laid out by COLREGs and local documents. Mark the ferry route in sea charts.
The ferry is surrounded by other vessels and/ or kayaks.	The ferry cannot decide on appropriate action and may linger or may collide with one or several vessels.	Communicate and signal the intentions of the ferry clearly to the surroundings. Simulation and testing of several operation scenarios to ensure appropriate behavior.

Table 4 Summary of the most critical hazardous events and risk reduction measures related to the failure of technical components.

Hazardous event	**Consequence**	**Risk reduction measures**
Blackout/ loss of power on the ferry.	No propulsion, loss of control and drifting.	Emergency anchor drop. Redundant battery system.
Failure of sensors, due to degradation, dirt, weather conditions, vandalism, etc.	Low awareness of the surroundings by the ferry may lead to collisions and loss of the ferry.	Sensors need to be distributed to ensure good coverage of the surroundings. Use of redundant sensors and redundant system types.
Failure of communication systems (internal, between components).	Delayed or missing sensor inputs, slow reactions times, or no actuation may lead to loss of control over the ferry.	Develop a robust communication hierarchy and architecture for the components. Use best practices and standards that exist. Employ state of the art error detection and handling mechanisms. Emergency (remote) power off mechanism.
Failure of communication systems (external	Loss of remote monitoring and control capability. Or	Have several redundant ways of communication with the Supervisor/ operations center. Robust and certified communication system.

Hazardous event	**Consequence**	**Risk reduction measures**
with shore control or other vessels).	inadequate communication with other vessels.	
Software failure or errors in the software for the control system, navigation system, sensor systems, etc.	Loss of situational awareness that may lead to a collision with other vessels, loss of control may lead to loss of the system.	Use of a standard software development approach and safety standards for software development, including thorough software testing, system simulation, verification, and validation. Separate critical functions on different software systems and embed them on different computers. Employ systems for anomaly detection of the behavior of the ferry and provide warnings to the shore supervisor. Establish software maintenance routines and management.
Failure of the battery and the battery cooling system.	May lead to overheating fire, and the formation of toxic gases.	Employ an intelligent energy management system capable to detect failures. Fire detection and fighting system that is adequate for the battery type.

Table 5 Summary of the most critical hazardous events and risk reduction measures related to security and cybersecurity of the ferry.

Hazardous event	**Consequence**	**Risk reduction measures**
The ferry is vandalized.	The ferry is damaged, and is not operational and not attractive.	Prevent physical intrusion and provide video surveillance of the ferry.
Ferry or shore control station is hacked or attacked through cyber-attacks.	The ferry is not controllable or operational.	Cyber secure implementation and design of the ferry system. Employ a cybersecurity management system. Monitor and detect abnormal system behavior.
Arson on the ferry.	Damages or loss of the ferry.	The design needs to account for fireproof components. No access to the inside of the ferry hull for passengers.

Table 6 Summary of the most critical hazardous events and risk reduction measures related to passenger safety.

Hazardous event	**Consequence**	**Risk reduction measures**
Passengers slip or fall.	Injuries and possible man overboard situations.	Clear communication of intentions of the ferry to the passengers. Provide required lifesaving equipment easily accessible and easy to use to the passengers. Provide an emergency button to call for help and assistance. Adequate deck design for safe and comfortable traveling.
Capsizing or damage to the ferry hull.	The ferry capsizes or is damaged leading to injuries of the passengers or further damages to the ferry.	Provide required lifesaving equipment easily accessible and easy to use to the passengers. Provide an emergency button to call for help and assistance. Establish emergency procedures and routines.

Hazardous event	Consequence	Risk reduction measures
		Hull and deck design should allow for enough time for a safe evacuation, i.e., emergency exit doors (openable without power) and watertight compartments.
Passenger falls overboard.	May lead to injuries or a casualty.	Provide required lifesaving equipment easily accessible and easy to use to the passengers. Provide an emergency button to call for help and assistance. Provide fences and ladders on the quay for getting out of water. Design bulwarks with sufficient height to prevent falling.
Admission system of the ferry fails.	More passengers on board the ferry than allowed. This may lead to overloading, stability problems and consequently to damages to passengers and the ferry.	Employ an intelligent and robust admission system and cameras to monitor the passengers. Security and cybersecurity management to prevent sabotage of the admission system.
Admission gates or ramp does not close on departure.	Passengers might fall into the water and/ or water may ingress in the ferry.	Design a hard-locked system that does not allow departure before the gates and ramp are closed. Monitor the ferry with a camera.

Table 7 Summary of the most critical hazardous events and risk reduction measures related to natural hazards.

Hazardous event	Consequence	Risk reduction measures
Strong wind, currents, and tides lead to drift off the ferry.	The ferry is not able to cross the channel or to dock adequately.	Monitoring of the environment (wind waves, currents) and stop operation if acceptable limits are exceeded.
Excessive motion of the quay when passengers are waiting or boarding.	Passenger injuries and/ or damages to the quay and the ferry.	Sufficient stable mooring of the quay. No operation during high waves and bad weather.
Lightning, solar storms.	May disrupt sensors, destroy them or lead to a blackout of the vessel.	Surge protection, shielding for electrical systems against lightning strikes. Provide critical system parts with extra power supply and independent circuits.
Sunlight/ background lights disturb visual sensors.	Loss of situation awareness may lead to a collision.	Use different types of sensors (e.g. IR; LIDAR, RADAR, etc.). Test the sensors in different light and weather conditions. Define operating hours with respect to darkness.

3.3. Challenges

Three groups of challenges were identified. The first challenge is related to hazard identification, risk analysis methods, and data availability. The second challenge is related to the risk assessment and is concerned with the determination of a baseline risk level. The third group of challenges is related to the regulatory framework.

With respect to the hazard identification, risk analysis methods and data availability, several challenges arise. For the preliminary hazard analysis, a simple checklist-based method was employed. For the detailed design, this simple checklist method may not be sufficiently detailed. Autonomous systems are highly complex with emergent properties [34]. A simple checklist approach may not identify interaction failures [35]. The system theoretic process analysis (STPA, [36]) or the functional resonance analysis method (FRAM, [37]) may assist in the identification of such failure modes and reveal additional hazardous events. Research indicates [38, 39] that STPA in combination with the traditional methods, such as failure mode and effects analysis (FMEA), leads to a more thorough analysis.

The NMA requires a detailed risk analysis [2] for permitting operation of autonomous ships and ferries. Traditional risk analysis methods do not capture interaction failures sufficiently. The timing aspect of events, for example, is often neglected [40]. Adapted and new methods for risk assessment are needed that can capture the timing aspects, the emerging properties and the particulars of software [4]. Software behaves deterministically, and failures will therefore not occur randomly, but will always occur when the software is faced with input that it is not designed to handle. Once removed such a failure cannot occur again.

With respect to the data used for risk analysis, this introduces additional challenges. Data on software errors cannot be used to find an average failure probability or distribution, as it is used traditionally in quantitative risk analysis. The autonomous ferry concept is currently tested in a prototype version in 1:2 scale. As a prototype, the experiences gained through the testing of the prototype may provide invaluable input to the risk and hazard assessment. New risk models and methods for quantifying and estimating such failures are needed. In addition, autonomous vessels may be designed differently with novel technical equipment, constraining the experience or data related to the operation that could be used as a basis for quantitative assessment or validation of assumptions. Therefore, methods for estimating necessary data for risk assessment are necessary. Simulations and accelerated testing may assist in these efforts.

Another data-related challenge is the assessment of the traffic data in the harbor channel, or in any fairway, in general. The assessment based on historical trajectory data itself is nowadays not a problem. Identifying vessels and boats in real-time through the combination of video, radar, and artificial intelligence-based detection algorithms are still subject to uncertainty and not fully reliable. Assessing the impact of the ferry on the traffic pattern may be challenging. For instance, smaller vessels and kayaks may attempt to go near the autonomous ferry, to have a better look at it or to test its reaction. This may change the whole traffic situation. Currently, it is not possible to predict such changes.

The determination of the acceptable risk level is challenging for several reasons. Firstly, the expectation from the NMA is that the risk level should be equivalent to the existing risk level for manned ferries. However, this risk level has not been quantified, it is only a result of the present, largely prescriptive regulations. This makes comparison difficult. Further, it may also be questioned if it is sufficient that the risk level is equivalent. Most likely, public opinion will be that the risk level should be considerably lower. Statistics from the emergency services can be used to learn from relevant accidents in the channel. However, it is difficult to determine what is the actual level of risk in this area of the harbor channel and for comparable systems. Hence, a requirement to a “similar” risk level is difficult to fulfill without excessive testing.

Lastly, the regulations as laid out by the NMA is challenging for the autonomous ferry. Several regulations prescribe functions and positions be taken over by human seafarers, c.f., [24-28]. Since there is no operator on board the ferry, the tasks must be carried out by the autonomous ferry itself or by the supervisor onshore. Demonstrating that a chosen solution is better than a human operator will be difficult and clear performance criteria are required for the evaluation. No certification or training requirements are laid out for the supervisor yet, and another challenge will be to identify necessary training measures and certification programs for such a ferry supervisor.

Several regulations refer to the installation of water-based firefighting systems [14, 18, 41]. The ferry is going to be operated with electricity provided by rechargeable batteries. Firefighting measures are necessary, but a challenge lies in the equivalent safety principle for demonstrating safe operation. Recently, vessels using battery systems have been approved for operation and it is crucial that the experience gained in the certification and operation of these vessels is shared and used for demonstration purposes.

4. Conclusion and further work

This paper presents the overall results of the preliminary hazard analysis for a small autonomous passenger ferry crossing the Trondheim harbor channel in Norway. The main hazards and envisioned risk reduction measures are summarized. These are associated with software failure, failure of internal and external communication systems, traffic in the channel, especially kayaks, passenger handling, and monitoring, and weather conditions.

In addition, this paper summarizes practical challenges encountered in the ferry project. These challenges are related to available risk analysis methods and data, determining and establishing an equivalent safety level, and some of the prescriptive regulations currently in use by the Norwegian Maritime Authority.

The ferry project is currently entering the detailed design phase. Hence, it will be necessary to identify and select suitable risk assessment methods and use them to ensure a safe ferry design and operation. For this purpose, close cooperation between the design teams and different stakeholders is necessary to ensure that efficient risk reduction measures are identified and sufficiently integrated into the design.

Acknowledgments

Thieme acknowledges the research project “Unlocking the potential of autonomous systems and operations through supervisory risk control (UNLOCK)” with The Norwegian Research Council as the main sponsor of project number 274441. Guo acknowledges the NTNU financed “Autoferry-Autonomous all-electric passenger ferries for urban water transport” project.

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