Fault Tree Analysis of the Autonomous Navigation for Maritime Autonomous Surface Ships

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ABSTRACT

The maritime industry has been progressing towards autonomous shipping with a main barrier and scepticism being on the safety assurance of the next-generation autonomous ships. This study aims to perform a safety analysis of the autonomous navigation of a Short Sea Shipping vessel. A conceptual system for the investigated of the system is proposed as reference, and input data for the Mean Time Between Failure of the most critical components are derived from the pertinent literature. Fault Tree Analysis is employed to calculate various metrics including the probability of failure, frequency of failure, and unavailability of the autonomous navigation function as the top event. This study results identified the critical components that contribute to the failure of the autonomous navigation function in next-generation unmanned Maritime Autonomous Surface Ships.

Keywords: *Maritime Autonomous Surface Ships, Autonomous Navigation, Fault Tree Analysis*

1. INTRODUCTION

The maritime industry is paving the way towards the adoption of Maritime Autonomous Surface Ships (MASS) with the vision of realising the new “Shipping 4.0” era (Rødseth et al., 2016). Shipping 4.0 is the outcome of the developments by the fourth industrial revolution concepts, which include Cyber-Physical Systems (CPSs) with embedded intelligent onboard equipment (Rødseth et al., 2016). MASS is considered a complex system of CPSs, which according to the International Maritime Organisation (IMO) (IMO, 2018, 2019), a MASS is ‘a ship which, to a varying degree, can operate independently of human interaction’ with the basic prerequisite of ‘securing at least the same levels of safety as conventional ships.’ Hence, MASSs are called to strive for higher safety levels in autonomous operations covering the whole spectrum of ship functions including navigation, propulsion, energy management, and communication.

The pertinent literature employed various safety analysis techniques to quantify the severity of the potential hazards in MASSs operations and mitigate its consequences by proposing appropriate risk control measures. (Wróbel et al., 2017) conducted a what-if safety hazard analysis to identify hazardous scenarios in autonomous ships navigation. (Thieme et al., 2019) conducted a preliminary hazard analysis (HazId) in the early design phase of a small autonomous passenger ship. (Man et al., 2015) identified the issues related with human factors for scenario-based monitoring and controlling of a remote unmanned autonomous vessel based on experts' assessment. (Wróbel et al., 2016; Zhou et al., 2019) employed Bayesian Belief Networks (BBN) to analyse potential hazards associated with a remotely controlled and unmanned vessel. Several studies employed a System-Theoretic Process Analysis (STPA) to develop risk models and demonstrated hazards' list for an autonomous or remotely controlled ship at open sea operations (Banda et al., 2019; Utne et al., 2020; Wróbel et al., 2019; Wróbel et al., 2018a, 2018b). (Wu et al., 2020) conducted Fault Tree Analysis (FTA) to assess the collision risk at encounter scenarios between unmanned and manned vessels.

This study aims to implement FTA for the autonomous navigation function of a Short Sea Shipping (SSS) cargo ship and to calculate the probability of failure of the autonomous navigation in good weather and day light conditions. The critical components of the function are identified through importance measures analysis and design enhancement recommendations are provided for the investigated system.

The remainder of this study is structure as follows. In Section 2, the developed methodology and its rationale are described. Section 3 delineates the case study details and the required input parameters. Section 4 presents and discusses the derived results. Lastly, Section 5 summarises the main findings and the conclusions of this study.

2. METHODOLOGY

The followed methodology to accomplish this study aim consists of six phases as presented in Figure 1. In the first phase, the description of the investigated system sought for the next-generation SSS autonomous ships is provided. This description forms the basis of this analysis and defines the subsystems and components as well as their interactions (Kristiansen, 2013; Rødseth & Tjora, 2014).

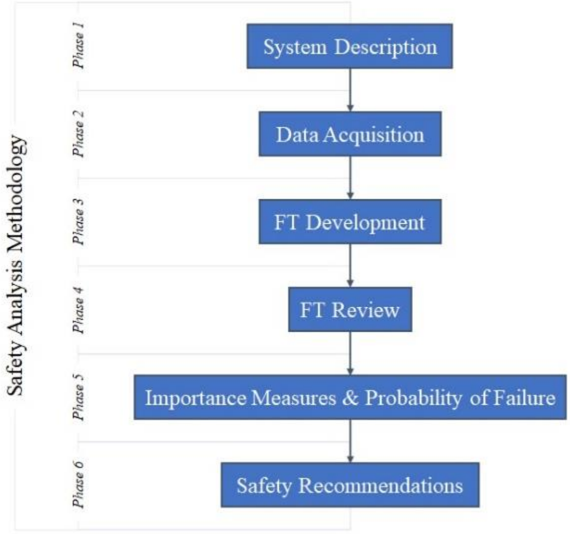

Figure 1 Methodology flowchart.

Phase 2 includes the acquisition of Mean Time Between Failure (MTBF) values from the pertinent literature for the investigated system components (hardware, software, sensors, actuators, etc.).

Phase 3 employs FTA implemented in the PTC Windchill software (PTC, 2021), considering as top event the failure of the autonomous navigation function in good weather and day conditions. FTA is one of the most widely employed safety analysis methods for both qualitative and quantitative evaluation of the system's probability of failure, unreliability, or unavailability (Aksu, 2019; Kuzu et al., 2019; Ung, 2019; Zhou et al., 2020). It is a top-down approach that uses probability theory and Boolean algebra, in which a single undesirable event is analysed by determining specific causes that can lead to the occurrence of that event.

During Phase 4, the developed Fault Tree (FT) was reviewed. This is an essential step for both the verification of the derived results and checking the soundness of the proposed recommendations. In Phase 5, the importance metrics and the probability of failure are estimated. The Birnbaum and Fussel-Vesely measures were considered indicating the components, the failure of which will most probably lead to the system failure, or which have the highest influence in terms of their failure rate on the top event probability of failure (Verma et al., 2010). Based on the importance measures analysis, safety recommendations are provided targeting to increase the availability of the critical components by introducing appropriate redundancy or introducing intelligent technologies for the monitoring and health assessment of the investigated system design in Phase 6.

3. CASE STUDY

3.1 System Description

The proposed methodology was applied to the case study of a next-generation autonomous SSS vessel. A cargo vessel of medium size servicing cargo transport between Europe's main ports at the North Sea was taken into account. This study only considers the voyage phases of the open-sea passages during transit, excluding the port approach and departure. Furthermore, an autonomy level 4 is considered according to the IMO categorisation (IMO, 2021), which implies an unmanned ship equipped with autonomous decision-making navigation systems.

The investigated system consists of hardware and software of various navigational components and subsystems. The main hardware includes marine computers and electronics, which are integrated with software consisting of various algorithms for path planning, voyage management, and collision avoidance. Subsystems provide all the necessary data required for ascertaining the required situation awareness of the surrounding environment and encounter situations, such as weather, underwater, surface, and the Own Ship (OS) state perception systems, and communication system. Navigational decisions made by the Autonomous Navigation System (ANS) are executed in the vessel propulsion control subsystem, where ordered commands are forwarded in the power plant and steering subsystems through wired communication. The power plant and steering subsystems are designed with sufficient redundancy (two main engines and steering gear) ensuring compliance with the prevailing class regulations (Veritas, 2019). The layout of the proposed system for the considered SSS vessel is provided in Figure 2.

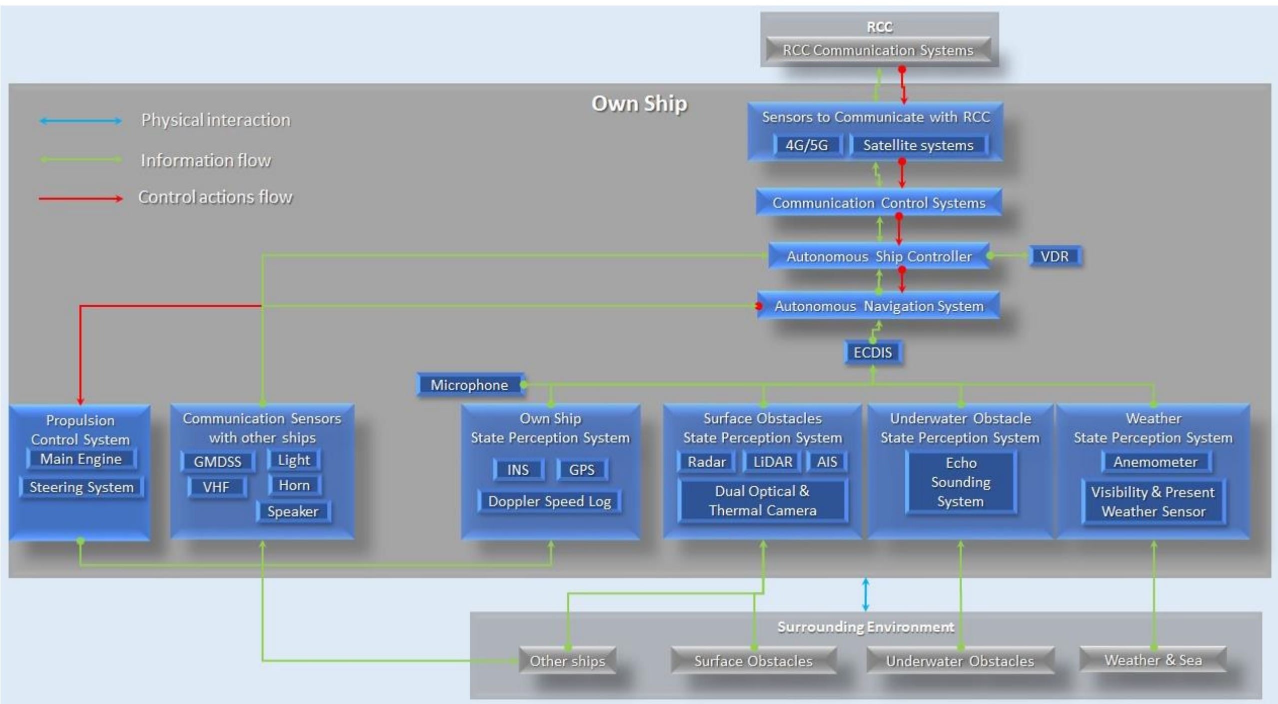

Figure 2 Reference layout of the ANS for the considered next-generation SSS MASS.

3.2 Analysis input and assumptions

This study used data for the MTBF of the autonomous navigation components, which were acquired from the pertinent literature. These parameters are presented in Table 1. Moreover, the analysis of this study only considered the SSS vessel operation in a scenario of good weather and daylight conditions. The analysis was conducted for operational time duration of 1 month, which is approximately 730 hours. More specifically, an operating profile of 12 hours operation at daylight and 12 hours anchoring at port during night was considered which translates into actual time of 1460 hours. Lastly, the interaction of the SSS vessel with the Remote-Control Centre (RCC) was not taken into account, thus failure of the RCC components were excluded in the analysis.

4. RESULTS & DISCUSSION

4.1 FT development & review

Based on the proposed system layout, the FT was developed considering the top event of the autonomous navigation function failure in good weather and daylight conditions as presented in Figure 3 and Figure 4. This FT consists of 40 basic events distributed in 7 levels. A total number of 12 AND gates were employed to represent the navigation sensors or subsystems/components. The derived probability of the autonomous navigation function failure (top event) is 0.414. The probability of the ANS failure is 0.412, whereas the power/propulsion system probability of failure is 0.0032, and the probability of the steering gear system failure is 0.000784. These results highlight that the ANS failure is the main contributor to the autonomous navigation function failure. The power and propulsion plant exhibits a small contribution to the autonomous navigation function failure, whereas the steering system has the smallest contribution.

4.2 Criticality importance measures & probability of failure

Critical design weaknesses and component failures in the investigated system can be investigated through the Fussell-Vesely and Birnbaum importance measures. Birnbaum indicates the rate of change in total risk due a basic event failure, whereas Fussell-Vesely indicates the percentage contribution of a cut set to the total risk (Van der Borst & Schoonakker, 2001). Table 2 presents the derived Fussell-Vesely and Birnbaum measures calculated for the most critical 22 components out of the total 28 components presented in Table 1.

Table 1 MTBF data for the investigated ANS critical.

No	Components	MTBF [hours]	Reference
1	Anemometer	131,400	(MicroStep-MIS)
2	Visibility & Present Weather Sensor	306,600	(MicroStep-MIS)
3	Echo Sounding System	105,120	(Kongsberg, 2012)
4	Radar	50,000	(Galati & Pavan, 2015)
5	LiDAR	100,000	(Quanergy, 2020)
6	Dual Optical & Thermal Camera	10,000	(TBT, 2021)
7	AIS	100,000	(Kongsberg, 2019)
8	GPS	1,234,605	(Synergy-Systems, 2017)
9	Doppler Sonar Velocity Log	2500	(Cirspb, 2021)
10	INS	200,000	(Safran, 2021)
11	Microphone	110,000	(Zenitel, 2021)
12	ECDIS	39,675	(DigitX, 2021)
13	Horn Loudspeaker	750,000	(Zenitel, 2021)
14	Ceiling Loudspeaker	750,000	(Zenitel, 2021)
15	VHF	50,000	(Danphone, 2021)
16	Light System	30,000	(Oxleygroup, 2021)
17	LTE	270,000	(Teltonika-networks, 2020)
18	Satellite Communication System	27,900	(SatMagazine, 2016)
19	Power Supply	90,000	(Teledynemarine, 2021)
20	PC Hardware	100,000	(Marinenav, 2021)
21	Software	10,000	(SINTEF, 2010)
22	Steering Gear	25,703	(Brocken, 2016; DNV, 2015)
23	Shafting	80,179	(Brocken, 2016; DNV, 2015)
24	Main Engine	13,881	(Brocken, 2016; DNV, 2015)
25	Fuel System	48,397	(Brocken, 2016; DNV, 2015)
26	Cooling water system	63,953	(Brocken, 2016; DNV, 2015)
27	Electrical system	60,360	(Brocken, 2016; DNV, 2015)
28	Diesel electric Generator System	149,223	(Brocken, 2016; DNV, 2015)

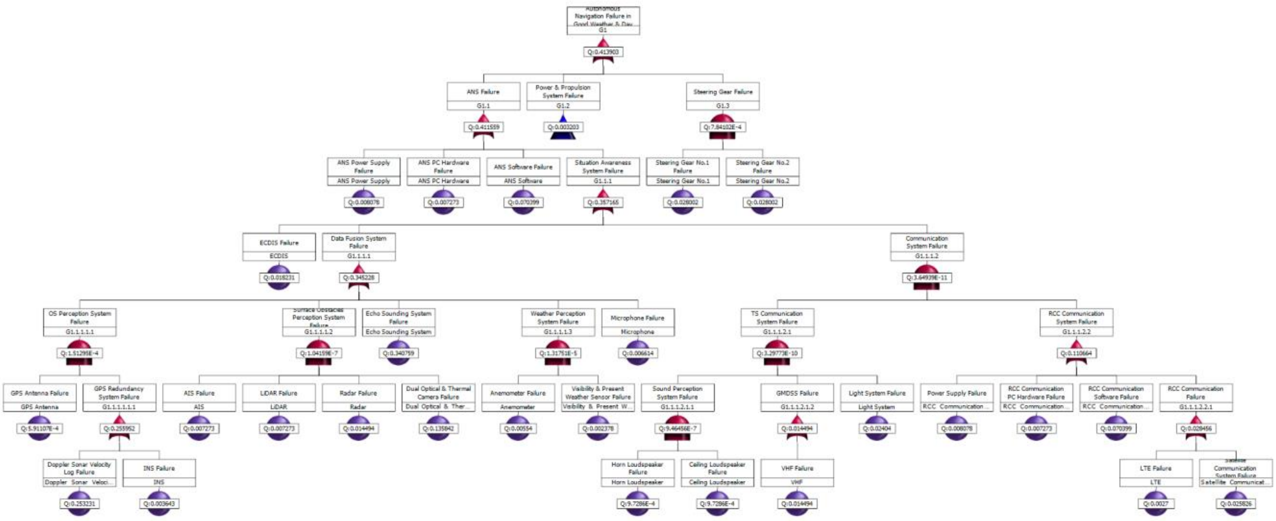

Figure 3 FT of the basic event of the Power/Propulsion System failure.

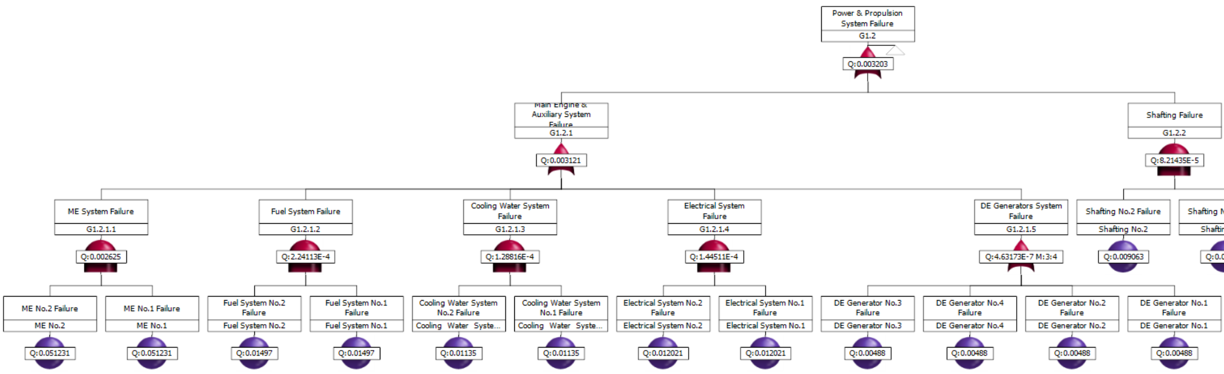

Figure 4 FT for the top event of autonomous navigation function failure considering the basic events of the ANS, power/propulsion system and steering gear system failures.

Table 2 Calculated FTA importance measures.

No	Event	Birnbaum [-]	Fussell-Vesely [-]
A	Echo Sounding System	1	0.75
B	ANS Software	1	0.15
C	ECDIS	1	0.04
D	ANS Power Supply	1	0.02
E	ANS PC Hardware	1	0.02
F	Microphone	1	0.01
G	GPS Antenna	0.26	$3.33\ 10^{-4}$
H	ME No.1	0.05	$5.76\ 10^{-3}$
I	ME No.2	0.05	$5.76\ 10^{-3}$
J	Steering Gear No.1	0.03	$1.72\ 10^{-3}$
K	Steering Gear No.2	0.03	$1.72\ 10^{-3}$
L	Fuel System No.1	0.01	$4.92\ 10^{-4}$
M	Fuel System No.2	0.01	$4.92\ 10^{-4}$
N	Electrical System No.1	0.01	$3.17\ 10^{-4}$
O	Electrical System No.2	0.01	$3.17\ 10^{-4}$
P	Cooling Water System No.1	0.01	$2.83\ 10^{-4}$
Q	Cooling Water System No.2	0.01	$2.83\ 10^{-4}$
R	Shafting No.1	$9.06\ 10^{-3}$	$1.80\ 10^{-4}$
S	Shafting No.2	$9.06\ 10^{-3}$	$1.80\ 10^{-4}$
T	Visibility & Present Weather Sensor	$5.54\ 10^{-3}$	$2.89\ 10^{-5}$
U	Anemometer	$2.38\ 10^{-3}$	$2.89\ 10^{-5}$
V	Doppler Sonar Velocity Log	$5.91\ 10^{-4}$	$3.29\ 10^{-4}$
W	INS	$5.91\ 10^{-4}$	$4.73\ 10^{-6}$

Based on the derives importance metrics, the critical components were grouped into various importance groups as presented in Figure 5. The ANS software and Echo Sounding System are found to be the most critical components. The next most critical groups include ECDIS, ANS power supply, ANS PC hardware, and microphone.

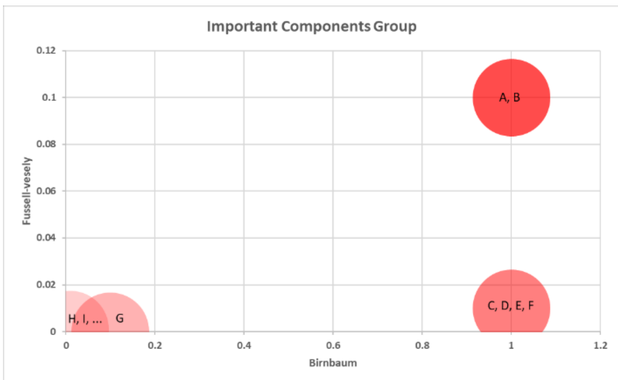

Figure 5 Components group based on the derived importance measures.

4.3 Safety recommendations

The identified system components support the safe decision-making and execution of the autonomous navigation function, which include route planning, voyage management, collision avoidance, and situation awareness. Failure of the ANS software, hardware, and power supply are most likely to lead into severe navigational accidents, such as collision with other ships, surface and underwater obstacles, and grounding, due to the absence of crew onboard to take control of the navigation. To ensure the investigated system safety, it is recommended to adding a backup of the identified critical ANS components including software, hardware, and power supply source, Echo Sounding System, ECDIS, and microphone.

Failure of weather sensors and inertial navigation system is expected to lead into navigational hazardous conditions; however, this analysis was conducted for good weather and daylight conditions, thus these components/systems were not found critical, especially when considering open sea navigation, where the traffic congestion is not dense.

Failure of other navigational components, such as AIS, LiDAR, Radar, Camera, VHF, Satellite Communication System, and LTE broadband, were not found to be critical. Although, Camera and LTE are much more dependent on the navigation conditions, these components are not found critical for the SSS vessel operation in good weather and daylight conditions.

Although redundancy of the safety-critical systems or sensors may secure enough safety levels of complex systems, such as the ANS (Felski & Zwolak, 2020; Wróbel et al., 2018a), this approach is not optimal in terms of cost-effectiveness. Additional recommendations include the use of advanced versions of critically important components and sensors with greater MTBF and the use of intelligent software such as sensor’s health monitoring in order to provide early alarm and maintenance schedule. Lastly, validation and verification of the conceptual software mentioned in the investigated system must be conducted in order to define their safety levels.

5. CONCLUSIONS

In this study, the safety of the autonomous navigation function was investigated by conducting FTA. A reference system was proposed and MTBF data of the most important components were acquired. For the reference system, a FT was developed for the top event of the autonomous navigation function in good weather and daylight conditions. The probability of failure of the autonomous navigation function and the criticality importance measures were calculated. Important components of the autonomous navigation were identified and grouped based on their criticality, whereas design recommendations were provided.

The main findings of this study are the following:

- The ANS and its situation awareness subsystem was found to mostly contribute to the autonomous navigation function failure.
- Various conventional navigation systems and sensors were found to be not critical for the autonomous navigation in good weather and daylight condition.

This study proposed a high-level system layout for the autonomous navigation of a next-generation unmanned MASS and identified its critical components. Considering that this analysis corresponds to an early design phase, additional design iterations and safety analyses are required to end up in the final design of the MASS ANS.

6. ACKNOWLEDGEMENTS

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7. ABBREVIATIONS LIST

AIS	Automatic Identification System
ANS	Autonomous Navigation System
BBN	Bayesian Belief Networks
CPS	Cyber-Physical System
ECDIS	Electronic Chart Display and Information System
FTA	Fault Tree Analysis
FT	Fault Tree
GPS	Global Positioning System
HazId	Hazard Identification
IMO	International Maritime Organisation
INS	Inertial Navigation System
LiDAR	Light Detection And Ranging
LTE	Long Term Evolution
MASS	Maritime Autonomous Surface Ships
MTBF	Mean Time Between Failure
OS	Own Ship
PC	Personal Computer
RCC	Remote-Control Centre
SSS	Short Sea Shipping
STPA	System-Theoretic Process Analysis
TS	Target Ship
VHF	Very High Frequency

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