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Improving Maritime Electronic Navigation Systems to Improve Collision Avoidance

CAPSTONE REPORT

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Abstract

Collisions at sea continue to be one of the most serious challenges facing the maritime industry, despite advances in marine electronic navigation systems. These electronic navigation systems can be improved with better collision avoidance algorithms to reduce marine accidents. This study reviews research in collision avoidance, mariner decision-making and electronic navigation systems since 2006. Military and commercial navigation system design and procurement personnel can benefit from this study to improve vessel safety and reduce losses.

Keywords: collisions, collision avoidance, decision-making, maritime, sea, rules of the road, navigation system, e-navigation, situational awareness

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Introduction to the Annotated Bibliography

Problem

For thousands of years, ships have been engaged in commerce, dating back at least as far as 3000 B.C. when the ancient Egyptians were known to build ships from wooden planks and use them in trade in the regions of modern-day Lebanon and Syria and throughout the Red Sea (Ward, 2010). Over the centuries, interactions between ships at sea, almost all under sail, were managed by informal procedures, local customs, or even luck, resulting in unintended collisions between vessels (Werner, 2017). With the advent of steam-powered ships in the mid-19th century, maritime laws and regulations governing ship interactions at sea were enacted to reduce accidents at sea (Werner, 2017). However, it was not until the early 1900s when international maritime regulations began to take hold, eventually evolving into the International Maritime Organization's (IMO's) Convention on the International Regulations for Preventing Collisions (COLREGs) at Sea, 1972 (International Maritime Organization, 2019a), which governs ship interactions in international waters around the world (Werner, 2017). The International Maritime Organization (IMO) is the United Nations' "specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships" (International Maritime Organization, 2019b, para. 1). Further, IMO is "the global standard-setting authority for the safety, security, and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented" (International Maritime Operations, 2019b, para. 2).

In just the last hundred years, technology has improved maritime safety and is reducing the number of accidents at sea (Allianz, 2017). The advent and harmonization of shipboard, integrated electronic navigation systems are enhancing navigation and related services for safety and security at sea (Grech & Lutzhoft, 2016). These systems include the echo sounder, which computes water depth using the speed of sound in water and the time difference between sound transmission and receipt (Coastal Data Information Program, 2019); radar, which determines range, velocity and angular direction of targets (Jenn, n.d.); the Global Positioning System (GPS), which can determine a receiver's exact position and, with that position, can determine speed, bearing, track, distance and many other parameters (Garmin, 2017); Electronic Chart Display and Information Systems (ECDISs), which contain all the relevant navigation information integrated with input from other systems (International Maritime Organization, 1995); and the Automatic Identification System (AIS), which is a tracking system that identifies and locates vessels (Boubeta-Puig, Medina-Bulo, Ortiz & Fuentes-Landi, 2012). These systems have improved safety and reduced the number of collisions and groundings mariners are experiencing at sea (Allianz, 2017), even as commercial shipping density continues to grow (United Nations, 2017).

Today, over 90% of the world's trade is being transported by the international shipping industry (International Chamber of Shipping, 2017). The world's merchant fleet of over 90,000 merchant ships moved over 10 billion tons of cargo in 2017 (International Chamber of Shipping, 2017). Commercial shipping is projected to increase by 3 – 5% each year (United Nations, 2017). The amount of global marine traffic makes it more difficult to detect or prevent critical or relevant situations like collisions (Boubeta-Puig et al., 2012). Even with improving technology, collisions are still occurring and, when combined with vessel sinkings, account for 16% of all marine claims, costing millions in damages and lost earnings (Allianz, 2018). Allianz (2017) notes that an overreliance on technology is one reason why accidents still occur.

With the volume of commercial shipping operating today, it is not surprising that the maritime industry is experiencing large numbers of losses and casualties each year (Boubeta-Puig et al., 2012), where a loss is defined as the amount recoverable under admiralty law when a vessel is lost or damaged (Raia, 2015). From 2008 to 2017, there were nearly 1,200 total losses and almost 26,000 casualties for merchant vessels, costing billions of dollars in lost revenue (Allianz, 2017). An estimated 75-96% of marine accidents are attributed to human error (Allianz, 2017). Of these accidents, collisions at sea are one of the major categories, second only to machinery damage (Allianz, 2017).

This is the environment in which the United States Navy is operating. With a force of 289 ships and submarines (United States Navy, n.d.-a), U.S. Navy ships are operating in close concert with this high density of marine traffic and high number of marine accidents. Despite operating ships with advanced technology in propulsion, navigation and combat systems, the Navy has been susceptible to collisions at sea (United States Fleet Forces Command, 2017). In 2017, there were three collisions involving U.S. Navy warships (United States Fleet Forces Command, 2017). These collisions cost the lives of 17 sailors, took three front-line warships out of operations for years, and incurred damages in excess of $360 million (Bateman, 2018). In each of these collisions, a loss of marine traffic situational awareness by the Officer of the Deck (OOD) on the Navy ship involved was a primary contributing factor to the collision (United States Fleet Forces Command, 2017). For example, in the *USS Fitzgerald* (DDG 62) collision, the complex radar systems were not operating within technical specifications and were not operated properly (Ziezulewicz, 2019). Thus, despite the use of sophisticated technology, the specific collision avoidance actions still rely on, and are carried out by, the mariner according to the situation and depend upon the mariner's experience level (Lei, Xiao, Wen, & Peng, 2018).

One solution that holds promise for addressing the losses associated with marine accidents is employing technology, like the concept of e-navigation, to improve mariner situational awareness and decision-making to avoid collisions (Pietrzykowski, Wolejsza & Borkowski, 2017); specifically, using technology to supplement current integrated electronic navigation systems to improve safety. The specific technology of focus for this research is integrated navigation systems, with an emphasis on effective displays of collision avoidance maneuvers. For the purposes of this research, integrated navigation systems' effective display of collision avoidance maneuvers will be defined as providing the necessary information to allow mariners to initiate action in ample time and with due regard of good seamanship to avoid collision (International Maritime Organization, 2003).

Purpose Statement

The purpose of this annotated bibliography is to present literature that addresses the problem of electronic navigation systems that do not provide clear, optimum recommendations to mariners to avoid collisions at sea once the risk of collision has been identified. Literature is presented on technology that can evaluate the risk of collision and provide analytical results for use by mariners to improve contact avoidance decision-making (Zhang, W., Kopca, C., Tang, J., Ma, D., & Wang, Y, 2017). Improved decision-making would assist in reducing the number of marine accidents (Pietrzykowski et al., 2017), which would save lives, reduce losses and reduce the financial liabilities in the commercial shipping industry (Allianz, 2018). The design of this study is a literature review, with the method of inquiry centered on the collection, sorting, review, annotation and analysis of selected research articles.

Research Question

How can shipboard, integrated navigation systems better display collision avoidance maneuvers to reduce the risk of collision?

Audience

While both commercial and military mariners can benefit from this study due to the focus on maritime collision avoidance, the specific audience for this research is the U.S. Navy and related stakeholders. This audience is divided into two distinct groups. The first group falls under the Deputy Chief of Naval Operations (DCNO) for Resources, Warfare Requirements, and Assessments, who directly influences the acquisition process for technology systems (United States Navy, n.d.-b). This study would heavily influence the initial capabilities document to support the material development decision, as well as the draft capability development document to support the development request for proposal (RFP) (Department of Defense, 2015).

The second group for this study is comprised of the defense contractors that would submit their respective proposals to satisfy the technical requirements that result from this study and the accompanying acquisition milestone documents. A defense contractor is "any individual, firm, corporation, partnership, association, or other legal non-Federal entity that enters into a contract directly with the DoD to furnish services, supplies, or construction" (32 CFR §158.3, n.d., para. 14). This study would inform the framework under which defense contractors could develop systems that would satisfy the requirements put forth in the request for proposal.

Search Report

Search strategy. I started my search strategy by looking at a general topic and breaking it down into what I thought were reasonable categories. My approach was to start with what I think is my overarching objective, which is to improve maritime navigation systems with collision avoidance. To that end, I broke this objective down into three lines of effort in terms of research categories: (a) mariner decision-making, (b) collision avoidance, and (c) marine navigation systems. I further started to divide my references into three main categories related to my problem. The first category addressed research on the human factors associated with collisions at sea by reviewing research associated with mariner decision-making. The second category of references with research directly related to the problem and solutions for collision avoidance. Finally, the third category contained research for possible solutions associated with the design of marine electronic navigation systems.

Key terms. Within each research category, I came up with search terms that I thought would identify reference sources relevant to the category. For the first category, I identified the search terms *decision-making*, *situational awareness*, *rules of the road*, *intuitive vs. analytical*, *avoiding collisions* and *assessing the risk of collision*. For the second category, I identified the search terms *collisions*, *maritime*, *sea* and *collision avoidance*. Finally, for my third category, I used the search terms *navigation systems*, *e-navigation*, *navigation system design*, *electronic navigation* and *situational awareness*.

Search engines and databases. Armed with my search terms, I started my search using the University of Oregon Research Guides in the Computer and Information Sciences category. During my first week, I conducted searches in the ACM Digital Library, IEEE Xplore, Academic Search Premier, CiteSeer, and MathSciNet databases and Google Scholar search engine to get a general sense for the scale of research literature that was available. I returned several sources and quickly recognized that I would not be hampered in my efforts by a shortage of research literature. During my second week, I focused exclusively on the Association for Computing Machinery (ACM) Digital Library and continued to search for references relevant to my first category, collision avoidance. This search identified several references that provided both context of the problem as well as specific focus to solutions I was considering for this problem.

In addition to the published research, I also searched for documents published by the U.S. Navy referencing the collisions that occurred in 2017. These documents were readily available in the Google Scholar search engine and I quickly located them using the search terms associated with the U.S. Navy ships involved in the collisions – *USS Fitzgerald* and *USS John S. McCain* (DDG 56).

Documentation Method. I used Zotero to document my search results. As a backup to Zotero, I utilized Microsoft Word to document results of specific word search combinations, as I found that various combinations of key words returned different search results. For example, in my first category of collision avoidance, using the search terms *collision* and *maritime* yielded different results than using the search terms *collision*, *sea* and *maritime*.

Research Evaluation Criteria. To evaluate the credibility of my references, I utilized the five characteristics that the Center for Public Issues Education (2014) recommends for consideration. These characteristics are authority, timeliness, quality, relevancy and bias.

Authority. For all but one of my references, I established authority by utilizing references that were predominantly presented at scholarly conference proceedings, published in professional journals, or were recognized as authoritative in the maritime field by the nature of the organizations or institutions to which the author(s) belonged. The one reference not presented in scholarly channels was an authoritative review of recent U.S. Navy collisions experienced in the western Pacific published by the Chief of Naval Operations. As such, I assess this reference to be on par with the authority of my scholarly references. An added benefit of this particular reference is that it provided the necessary context for the intended audience of this study. No references were obtained from either newspapers or blogs.

Timeliness. In all but one case, I utilized references from 2012 and beyond, with eleven references being published within the last five years. This ensured the content of the references reflected current technologies and trends, which was particularly important for references within the category of *marine electronic navigation systems*. In this category, one reference from 2006 was relevant as the theory it presents regarding course optimization to avoid collision is still relevant with current research.

Quality. To ensure the highest quality of references utilized, I predominantly limited my references to those obtained either via the University of Oregon Library System research databases or through government sources. A thorough review of my references ensured that, accounting for country of origin, grammar, spelling and punctuation were consistent with the quality expected of scholarly references. Charts, graphics, and diagrams are well presented in each reference.

Relevancy. By establishing reference categories, I ensured all of the references utilized in my study were relevant to the problem. By grouping references used in this study into three categories relevant to the problem, I was able to ensure that each reference was directly applicable to key a key aspect of the problem central to this study. The content of each reference was appropriate to the category under which it was cataloged.

Bias. The nature of the problem precludes overwhelming author bias, as most elements of the problem are fact-based. However, I thoroughly reviewed each reference used in my annotated bibliography to ensure no particular bias was presented. I read each reference's introduction and conclusion and observed no indications of bias in any of the references.

Annotated Bibliography

Introduction to the Annotated Bibliography

This annotated bibliography contains 14 scholarly references and one authoritative reference that address current research in the field of collision avoidance at sea. This field is relevant to the U.S. Navy, given the recent string of collisions experienced in 2017 (United States Fleet Forces Command, 2017), as well as to the maritime industry at large (Allianz, 2017). All of these references are assessed as timely and relevant to the field of research. These references are broken into three categories: (a) mariner decision-making references, which capture research related to the decision-making process of mariners leading up to a collision, (b) collision avoidance references, which capture research related to technology and techniques to identify collisions, and (c) marine electronic navigation systems references, which captures research associated with systems used to operate ships at sea.

Each reference in the annotated bibliography contains a citation, an abstract and a summary. Where applicable, in the absence of a published abstract, a summary is provided by the author of this annotated bibliography instead. Each category of references addresses some facet of collision occurrences. Together, these references will provide the necessary context and focus to address how navigation systems can be improved for use by mariners to reduce the risk of collisions at sea.

Mariner Decision-Making

Department of the Navy. (n.d.). *Memorandum for distribution.* (Report on collisions). Washington, DC: Office of the Chief of Naval Operations. Retrieved 6 April 2018 from: http://s3.amazonaws.com/CHINFO/USS+Fitzgerald+and+USS+John+S+McCain+Collision+Reports.pdf

Author summary. Note: this abstract was written by the author of this annotated bibliography in the absence of a published abstract. This paper provides an executive-level summary of the sequence of events, root causes and contributing factors that led to the collisions between (1) the *USS Fitzgerald* (DDG 62) and *M/V ACX Crystal* and (2) the *USS John S. McCain* (DDG 56) and *M/V Alnic MC*. Failures identified included: (a) planning for safety, (b) adhering to sound navigation practices, (c) complying with the International Nautical Rules of the Road, (d) executing basic watchstanding practices, (e) operating with sufficient proficiency and knowledge of systems, (f) properly using available navigation tools, and (g) responding deliberately and effectively in extremis. Both collisions occurred in the western Pacific in the U.S. Navy's Seventh Fleet area of responsibility. The collisions resulted in the deaths of 17 Sailors, took both warships off the front lines from operations, and cost hundreds of millions of dollars in repairs.

Summary. The author wrote this article to provide a detailed analysis of the collisions involving *USS John S. McCain* and *USS Fitzgerald* in 2017. This analysis was generated from investigations conducted by U.S. Navy officials. These base investigations remain classified; however, in an effort to address the issue with the public, the Office of the Chief of Naval Operations published an unclassified compilation of these investigations for consumption by the public. These investigations, conducted by subject matter experts brought in from across the fleet, are extremely thorough. The author details the description and sequence of events, the immediate results of the collisions, and the search and rescue efforts for each event, including diving and recovery actions for each ship during its transit home and return to port. Of note, several of the failures contributing to the accidents identified by the Navy include failure to plan for safety, failure to adhere to sound navigation practices, failure to properly use available navigation tools, failure to adhere to COLREGs, and failure to respond deliberately and effectively when in extremis. The author concludes with the findings from each collision, focusing on training, seamanship and navigation, leadership and culture, and, in the case of *USS John S. McCain*, crew fatigue.

This source is relevant to this study because it provides real-world context and perspective on the need for improved collision avoidance capability to the primary audience for this study. Specifically, this source highlights the need for improved situational awareness and the need for clear maneuvering guidance in extremis operating in proximity with other vessels.

Jin, L., Luo, Z., & Gao, S. (2018). Visual analytics approach to vessel behavior analysis. *The Journal of Navigation, (71)*5, 1195-1209. Retrieved from: https://doi.org/10.1017/S0373463318000085

Abstract. Vessel behavior analysis plays an important role in maritime situational awareness. However, available technology still provides only limited approaches to vessel behavior analysis. In this paper, we propose a visual analytics framework to interactively explore the characteristics of vessel behavior by means of integrating visualization with data mining and a human-computer interaction controlling model, which combines human insight with the enormous storage and processing capacities of computers to gain insight into vessel behaviour. In addition, we provide multiple views for visually analyzing vessel trajectories, densities and speeds. Case studies with 15 days' AIS data collected from the middle Hankou channel to Yangluo channel in the Yangtze River demonstrate the effectiveness of our approach.

Summary. In this reference, the authors explore the characteristics of vessel behavior by means of integrating data mining with visual analytics, which allows Vessel Traffic Services (VTS) supervisors and operators to combine their experience with data and processing to gain insight into vessel behavior, or mariner decision-making. The authors assert that this approach will allow VTS supervisors and operators to directly interact with the data and allow them to make well-informed decisions in complex navigation situations. The authors focus on combining data mining with visualization technology to build interactive models for vessel behavior analysis, factoring in the multi-dimensionality of vessel behavior data including vessel trajectories, densities, and speeds.

The authors outline their visual analytics framework with detailed explanations of feature modeling for vessel behavior, including methodologies for visual analysis of the features and threshold for impacts to control human-computer interactive control. To validate their model, the authors conducted testing using historical AIS data collected from middle Hankou channel to Yangluo channel in the Yangtze River in 2015. The authors broke the data into three datasets, with AIS records numbering 100 thousand, 520 thousand, and 660 thousand, respectively. The authors show how the data visualizations can be modified based on setting cluster thresholds, setting the attenuation threshold of kernel density estimation, and setting the grid parameters. These adjustments successfully allow the user to obtain the information of vessel behavior more comprehensively, clearly and intuitively. The authors conclude that data mining and visualization technology can be combined to create interactive models of vessel behavior analysis that highlight the importance of understanding all the processes that happen in maritime navigation.

This source is relevant to this study because it demonstrates how visualizations can be employed to improve understanding of vessel behavior, and by extension, mariner decision-making. Similar visualization techniques can be utilized on an individual ship basis to better understand complex navigation situations to improve decision-making by mariners to avoid collisions.

Mohovic, D., Mohovic, R. & Baric, M. (2016). Deficiencies in learning COLREGs and new teaching methodology for nautical engineering students and seafarers in lifelong learning programs. *The Journal of Navigation, (69)*4, 765-776. Retrieved from: https://doi.org/10.1017/S037346331500096X

Abstract. The Faculty of Maritime Studies, University of Rijeka, Croatia, manages the European Union (EU) project "Avoiding Collisions at Sea" (ACTs). The project is funded by the European programme "Leonardo da Vinci". Other maritime education and training institutions participating in this project come from Great Britain, Spain, Slovenia, Bulgaria and Turkey. The purpose of this research was to identify skill gaps in knowledge and teaching of COLREGs (International Regulations for Preventing Collisions at Sea 1972 – Rules) for nautical Bachelor of Science (BSc) students and experience deck officers. The analysis of the research on marine accidents has identified vessel collisions as one of the most frequent types of accidents. Further research showed that human error and misinterpretation of the Rules are the most frequent reasons for vessel collisions. Using a questionnaire, nautical students/ navigating cadets and navigating officers' understanding of the Rules was tested. The results showed skill gaps in understanding of some parts of the COLREGs due to wrong interpretation and application of the Rules. The authors claim that it is possible to improve the professional competence of navigating officers by applying proper learning methods using real-life scenarios and e-learning.

Summary. In this reference, the authors identify that one of the most prevalent causes for collisions at sea is incorrect application of COLREGs. Through a literature review, the authors show that collisions remain one of the most frequent types of marine accidents at sea, and that the reason for these collisions is most frequently human error through a failure to observe COLREGs. In an attempt to understand this failure, the authors conduct research utilizing a questionnaire, workshops using 102 participants, and collision research using Marine Accident Investigation Branch (MAIB) accident reports from 14 collisions occurring between 2006 to 2012.

Questionnaire results show that Rule 6 (Safe speed), Rule 10 (Traffic separation schemes), Rule 13 (Overtaking), Rule 14 (Head-on situation), Rule 17 (Action by stand-on vessel), Rule 18 (Responsibilities between vessels) and Rule 19 (Conduct of vessels in restricted visibility) are hard to understand. Furthermore, these results are consistent between navigation students and experienced seafarers. When compared to the collision research, the authors are able to identify which rules are most frequently broken in collisions and note that these results are in contrast to the questionnaire results. Collision research shows that Rule 7 (Risk of collision), Rule 5 (Look-out) and Rule 8 (Action to avoid collision) are most frequently broken. Rule 6 and Rule 19 are broken in 60% of cases analyzed and Rule 17 and Rule 18 are broken in 40% of cases analyzed. The authors conclude that there is generally a lack of a full and complete understanding of COLREGs, and that new teaching methodologies to improve scenario-based training for mariners are needed.

This source is relevant to this study because it reaffirms the human error present in mariner decision-making which manifests itself through a lack of complete understanding of COLREGs. Understanding which rules mariners are most challenged with can influence design and development of contact avoidance algorithms in navigation systems.

Schroder-Hinrichs, J., Hollnagel, E., & Baldauf, M. (2012). From Titanic to Costa Concordia – A century of lessons not learned. *WMU Journal of Maritime Affairs, 11*(2) 151-167. Retrieved from: https://www.researchgate.net/publication/257804451_From_Titanic_to_Costa_Concordia-a_century_of_lessons_not_learned

Abstract. The recent foundering of the Costa Concordia in January 2012 demonstrated that accidents can occur even with ships that are considered masterpieces of modern technology and despite more that 100 years of regulatory and technological progress in maritime safety. The purpose of this paper is, however, not to speculate about the concrete causes of the Costa Concordia accident, but rather to consider some human and organizational factors that were present in the Costa Concordia accident as well as in the foundering of the Titanic a century ago, and which can be found in many other maritime accidents over the years. The paper argues that these factors do not work in isolation but in combination and often together with other underlying factors. The paper critically reviews the focus of maritime accident investigations and point out that these factors do not receive sufficient attention. It is argued that the widespread confident in the efficacy of new or improved technical regulations, that characterizes the recommendations from most maritime accident investigations, has led to a lack of awareness of complex interactions of factors and components in socio-technical systems. If maritime safety is to be sustainably improved, a systemic focus must be adopted in future accident investigations.

Summary. The authors of this paper identify the human and organizational factors in the maritime industry that have contributed to accidents at sea. Dating back to the loss of the Titanic in 1912, the authors compare and contrast that tragedy with the loss of the cruise ship Concordia, which grounded in 2012. By reviewing the factual information of both accidents, the authors identify the similarities between both. With similarities identified, the authors then evaluate them from several perspectives that are broadly labeled *human factors issues*. Between these two events, the authors identify the most prevalent factors that contributed to the accidents. These factors include: (a) authority gradient, the distribution of decision-making and the balance – or imbalance – of authority and power in a group or organization and the resulting influence on communications, (b) group think and the desire for harmony, (c) cognitive hysteresis – resistance to revising a situation assessment, (d) unanticipated consequences of new technology, (e) organizational influences, and (f) efficiency-thoroughness trade-off, which the authors identify as balancing the time and measures to ensure safety operations with economic considerations. The authors review how each factor influenced the accidents of both the Titanic and the Concordia and they also provide additional examples from other maritime accidents. The authors conclude that if these factors are understood by investigators of maritime accidents, as the factors contribute to accidents, their root causes can then be corrected, thus improving maritime safety.

This source is relevant to the study because it identifies accident factors beyond human error that must be considered by future collision avoidance algorithm displays that are integrated into navigation systems. Five of the six factors, organizational influences being the lone exception, have direct relevance to the future design of collision avoidance displays.

Weng, J., Li, G., Chai, T., & Yang, D. (2018). Evaluation of two-ship collision severity using ordered probit approaches. *The Journal of Navigation, (71)*4, 822-836. Retrieved from: https://doi.org/10.1017/S0373463317000996

Abstract. This study develops an ordered probit model to evaluate the factors influencing two-ship collision severity using ten years' ship collision accident data from Fujian sea areas. The model results show that the involvement of big ships has the largest impact in increasing the probability of a serious accident if both ships involved in the collision are cargo ships. We found that the season of spring, poor visibility and night time periods are more likely to be factors in high severity levels of ship collision. The results also reveal that lookout failure plays a decisive role in increasing serious accident risk compared with other types of human errors. The results of this study may be beneficial for policy-makers in proposing efficient strategies to reduce the likelihood of serious ship collisions.

Summary. In this study, the authors evaluate ship collision accident data between 2004 and 2014 for collisions that occurred in the Fujian Sea area. With the understanding that collisions are a major type of ship accident occurring in the sea areas around China, the authors evaluate the effects of influencing factors on collision severity using probit techniques. Ordered probit models, a type of regression where the dependent variable has a natural ordering with discrete values like poor, good and excellent, are used in this study because this type of analysis is able to investigate the marginal effects of influencing factors on accident severity. This study establishes the collision severity as the ordered response with random error associated with the continuous descriptor assumed to follow a normal distribution. The authors determine the probability of ship collision belonging to a specific accident severity using mathematical formulas that utilize coefficients that help interpret the effects of influencing factors on ship collision severity. Positive signs are used to indicate a higher collision severity, while negative signs indicate the opposite.

Each recorded data element for every accident is extracted from the database over the period of interest. These elements comprise three different categories of information: (a) accident characteristics, (b) environmental characteristics, and (c) accident cause factors. Collision severity was categorized into three levels: (a) less serious, (b) serious, and (c) very serious. The authors evaluated a total of 528 collisions and depicted the results in tabular and graphical format. The results of the analysis show that collision severity is statistically influenced by several factors, each with a positive valued coefficient. These factors are ship types; operational conditions like visibility, accident location and time; and the most significant - human error.

This source is relevant to this study because it captures the statistically significant factors that influence collisions, including the most significant, which is human error. A thorough understanding of these factors can then be utilized to modify collision avoidance algorithms. For example, if collision severity is higher with ship types like cargo ships, bulk carriers or liquid nitrogen gas carriers, then predefined minimum range values that define the CPA can be adjusted accordingly when encountering these types of vessels at sea.

Collision Avoidance

Boubeta-Puig, J., Medina-Bulo, I., Ortiz, G., & Fuentes-Landi, G. (2012). Complex event processing applied to early maritime threat detection. Proceedings from *The 2nd International Workshop on Adaptive Services for the Future Internet and 6th International Workshop on Web APIs and Service Mashups* (pp. 1-4). New York, NY: Association for Computing Machinery. https://doi.org/10.1145/2377836.2377838

Abstract. In recent decades the globalization has caused a huge increase of ship movements carrying goods and passengers between countries. It makes quite difficult to detect manually critical or relevant situations that may occur in marine traffic. In this paper, we propose an event-driven service-oriented-architecture that combines the complex event processing and data distribution system, building a high performance and available system for analyzing and correlating data provided by ship's automatic identification systems in real time. This architecture will be able to detect automatically, and as soon as possible, abnormal situations occurred in seas all over the world. For this, a set of complex event patterns for detecting AIS hijacking or failure, as well as ship engine malfunction or ship collision is proposed and defined in this work.

Summary. The authors propose an event-driven, service-oriented architecture that combines complex event processing and a data distribution system to allow users to detect defined events like AIS hijacking or failure, ship engine malfunction, or ship collision. By incorporating specific elements of an information stream that is readily available to users world-wide, for example from AIS, the authors are able to identify complex events by analyzing and correlating basic information and related events. The authors provide written code examples that capture a ship's positional information. Their proposed architecture would take such information, integrate it with other basic events from other information systems, store it in a Data Distribution System, and then analyze the data to identify specific, complex events that are occurring in real-time. These events, once identified, would then trigger pre-planned responses for users.

For ship collisions, the proposed complex event pattern would be to detect an event (a collision) when a ship's speed is greater than one knot and its position is the same as another ship's position. The authors conclude that this proposed architecture can be readily used for automatic, early detection of maritime threats in real-time.

This source is relevant to this study because it demonstrates the ability to leverage existing information streams to facilitate detection of marine accidents. While this source focuses on detection of the collision as an event, a natural extension could be to detect potential collisions before they occur when certain thresholds are exceeded.

Erol, S., Demir, M., Cetisli, B. & Eyuboglu, E. (2017). Analysis of ship accidents in the Istanbul Strait using neuro-fuzzy and genetically optimised fuzzy classifiers. *The Journal of Navigation, (71)*2, 419-436. Retrieved from: https://doi.org/10.1017/S0373463317000601

Abstract. Marine accident analysis is important for ships passing through narrow, shallow and busy waterways. This study analyses the accidents which have occurred in the Istanbul Strait and proposes both quantitative and qualitative assessments of marine accidents. Marine accidents occurring in the Istanbul Strait are analysed by using a method based on neuro-fuzzy and genetically optimised fuzzy classifiers. It can be concluded that accident severity increases when poor weather conditions prevail in the Strait regardless of ship size. Therefore, solutions to reduce unwanted events should be prioritised by accounting for weather conditions and the capacity of the vessels. This analysis indicates that the safety level would be significantly improved if all the vessels follow the passage guidelines.

Summary. In this paper, the authors utilize Artificial Intelligence (AI) methods to identify the most significant factors contributing to marine accident severity in the Istanbul Strait, the body of water connecting the Black Sea to the Mediterranean Sea. Because this is one of the most heavily transited and most dangerous waterways to navigate in the world, there is a need to minimize the number of accidents in the Istanbul Strait to improve safety and limit damages and associated costs. The authors use the accident archives from the Turkish Republic's Ministry of Transport, Maritime Affairs and Communications and weather condition data from the Turkish State Meteorological Service to prepare the model input. Model output uses the IMO's definition of accidents. Basic parameters used for analysis include Gross Registered tonnage (GRT), ship length overall (LOA), Sea Wave Height (LW) and Daily Average Windspeed (DAWS). Of the 880 marine accidents between 2001 and 2015, only the 135 marine accidents with matching weather conditions are used. Some AI techniques, detailed in the study, are used for classifying accident data.

The results show that as LOA increases, the severity of marine accidents rises. Similarly, as weather conditions deteriorate, the severity of marine accidents can increase. Thus, the authors conclude that these two parameters should be the controlling parameters for Turkish authorities. With these conclusions, the authors pose several precautions that could be implemented to decrease the number and consequences of maritime accidents in the Istanbul Strait, including implementation of safety rules related to weather conditions and implementation of risk reduction solutions such as ship size limit.

This source is relevant to this study because similar analysis could be conducted focusing on specific platform types, like U.S. Navy Arleigh Burke-class destroyers. The results of these AI methods would then allow for tailored manipulation of algorithms in navigation systems to adjust safety margins associated with the user-determined Closest Point of Approach (CPA) based on both weather conditions and the size of vessels operating in proximity of the user.

Fang, M., Tsai, K. & Fang, C. (2017). A simplified simulation model of ship navigation for safety and collision avoidance in heavy traffic areas. *The Journal of Navigation, (71)*4, 837-860. Retrieved from: https://doi.org/10.1017/S0373463317000923

Abstract. Based on our previously developed ship collision avoidance steering systems, this paper develops a more extensive collision avoidance decision-making system for non-uniformly moving ships. A real-time simulator based on the Six-Dimensional (6D) Manoeuvring Modelling Group (MMG) model is used to simulate the ship's motion. To validate the manoeuvring mathematical model, sea trial measurements of a container ship (C-3) have been selected. This study incorporates Nomoto's second-order model into a numerical model to calculate the turning characteristics of the ship. The manoeuvring indices of Nomoto's model are the knowledge base of the simplified ship simulation model. To verify the ship collision avoidance system with respect to different traffic factors, simple and complex collision avoidance cases have been designed in fast-time simulations with multi-ship encounter conditions. The simplified simulation model developed here can quickly determine the helm angle when the ship makes a collision avoidance manoeuvre, which is helpful for the safety of ship navigation in heavy traffic areas.

Summary. The authors build on previous research and further analyze the ability to compute optimal rudder/helm orders to optimize course maneuvers to avoid collisions. By using a simplified second-order equation of motion model, the authors are able to describe the turning characteristics of a large container ship. The model uses the Six-Dimensional (6D) maneuvering mathematical techniques based on the Manoeuvring Modelling Group (MMG) model developed separately. In conjunction with the United Ship Design and Development Centre Manoeuvring System (UMS), a research version, real-time simulator, the authors use the equation of motion to develop a database that incorporates ship motion along three coordinate systems that account for waves, ship motion and gravity.

To validate their model, the authors select the sea trial measurements of a container ship in the Taiwan Strait. Using defined International Maritime Organization (IMO) standards, the authors are able to compare actual ship performance data versus mathematical projections obtained from the model. Model projection agreement with actual sea trials data is excellent and also in compliance with IMO ship performance standards. Results, obtained for various rudder angles and ship speeds, are depicted graphically, and display the advance and transfer the ship would experience for various rudder/speed combinations. With the data, the authors are able calculate rudder angles needed at a given ship’s speed to avoid a collision at a predefined distance.

The authors exercise their model in simple and complex versions of ship interactions defined by COLREGs – head-on, meeting, and overtaking. In each interaction, the authors are able to determine the time needed to initiate a collision avoidance maneuver, using an optimal rudder angle, to ensure the ships involved do not close within the predefined distance, 300 meters in this study. Thus, the authors conclude that the simplified model can be used to determine optimum rudder angles to support collision avoidance.

This source is relevant to this study because it validates mathematical optimization of a ship parameter to avoid a collision. This concept can be extended to other ship parameters, such as speed and heading, to further optimize maneuvers to avoid collisions.

Lei, P., Xiao, L., Wen, Y., & Peng, W. (2018, October). CAPatternMiner: Mining ship collision avoidance behavior from AIS trajectory data. Proceedings from: *The 27th ACM International Conference on Information and Knowledge Management.* (pp. 1875-1878). New York, NY: Association for Computing Machinery. https://doi.org/10.1145/3269206.3269221

Abstract. The improvement of collision avoidance for ship navigation in encounter situation is an important topic in maritime traffic safety. Most research on maritime collision avoidance has focused on planning a safe path for a ship to keep away from the approaching ship under the requirements of the International Regulations for Preventing Collision at Sea (COLREGs). However, the specific anti-collision actions are actually carried out by the navigators' own experience according to the local encounter situation.

In this paper, different from the existing works, we discover the collision avoidance behavior from real ships' movement, i.e., AIS trajectory data. However, the uncertainty of maritime trajectory data brings the challenge of collision avoidance behavior mining. To achieve our goal, we propose CAPatternMiner to provide a framework to discover the ships' anti-collision behavior, which is effective in the encounter situation, and generate the discovered behavior in form of collision avoidance pattern. Furthermore, a prototype of CAPatternMiner is built for pattern analysis and visualization and also benefits a deeper understanding of collision avoidance behavior on maritime traffic. The proposed framework will be applied to the developing of patter-aware collision avoidance system to improve the maritime traffic safety.

Summary. In this paper, the authors propose evaluation of collision avoidance patterns that capture behaviors actually executed by navigators on ships. They assert that this evaluation would lead to a better understanding of actions actually taken by ships' navigators to effectively and successfully avoid collisions. These maneuvers, which may or may not be in compliance with COLREGs, will provide the foundation for further development of pattern-aware collision avoidance systems. To collect this data, the authors establish a framework for a software product called CAPatternMiner. This framework utilizes real-world AIS trajectory data from a specific geographic area to identify conflict events (collision situations). The authors limited their study to conflict events where the range between ships was within a user-defined circle of five kilometers and binned the resulting data into the three encounter situation classifications identified by COLREGs: head-on, crossing, and overtaking. For each category of events, CAPatternMiner is able to discern which actions are taken by each ship to avoid collisions.

The authors evaluated six months of AIS data that contain trajectories for 170,770 ships. In this data set, the authors identify 10,794 conflict events (collision situations) for analysis. CAPatternMiner successfully identified a number of different behavior patterns taken by ships for collision avoidance, not all consistent with the guidance and recommendations provided in COLREGs. Examples of behavior patterns include altering course and/or speed. When such patterns are not in compliance with COLREGs, they highlight decision-making by mariners to avoid entering collision situations. The authors conclude that this information will provide insight into real-world collision avoidance behavior, which will influence the development of effective and practical pattern-aware collision avoidance systems.

This source is relevant to this study because it highlights the ability to utilize current technology information streams to recognize collision situations. In addition, with better understanding of collision avoidance maneuvers taken by mariners, course optimizations can be improved for collision situations that are identified at ranges in excess of those where COLREGs normally applies.

Lisowski, J. (2013). Optimal and game control algorithms of a ship in collision situations at sea. *Control and Cybernetics, 42*(4), 773-792. http://link.galegroup.com/apps/doc/A416403070/AONE?u=s8492775&sid=AONE&xid=69ff2790

Abstract. This paper presents an application of selected methods of optimal and game control theory to determine own ship safe trajectory when passing other ships encountered in good and in restricted visibility at sea. Five algorithms for determining safe trajectory of the own ship in a collision risk situation: non-cooperative positional game, non-cooperative matrix game, cooperative positional game, dynamic optimization, and kinematic optimization are compared. The analysis is illustrated with examples of computer simulations of the algorithms to determine safe and optimal own ship trajectories in the real navigational situations at sea.

Summary. In this paper, the authors evaluate five algorithms for determining optimal ship maneuvers in a complex environment involving 47 other vessels. The algorithms considered for determining ship control strategies in a collision situation are non-cooperative positional game (NPG), non-cooperative matrix game (NMG), cooperative positional game (CPG), dynamic optimization (DO), and kinematic optimization (KO). Each algorithm utilizes a specific method of optimization, either linear or dynamic programming, as well as a specific form of trajectory, either game or optimal. Each algorithm is carried out in computer simulations using examples from real-world navigation scenarios with nine and 47 ships. For each scenario, the ship's planned navigation track and the track determined by the respective algorithm are depicted using a top-down view of the situation. From the analysis, the authors conclude that the DO algorithm is the most suitable one among those considered to constitute the computer assisted method for supporting the navigator in collision situations.

This source is relevant to this study because it validates the ability of algorithms to handle the high contact density often encountered in heavily trafficked sea lanes.

Qinyou, H., Qiaoer, H., & Chaojian, S. (2006). A negotiation framework for automatic collision avoidance between vessels. Proceedings from: *The IEEE/WIC/ACM international* *conference on Intelligent Agent Technology* (pp. 595–601). Hong Kong, China: Institute of Electrical and Electronics Engineers (IEEE) Computer Society. https://doi.org/10.1109/IAT.2006.19

Abstract. Automatic vessel collision-avoidance systems have been studied in the fields of artificial intelligence and navigation for decades. And to facilitate collision avoidance decision-making in any two-vessel encounter situation, several expert and fuzzy expert systems have been developed. However, none of them can negotiate with each other as seafarers usually do when they intend to make a more economic overall collision-avoidance plan in the COLREG-HIGH-COST situations where collision avoidance following the International Regulations for Preventing Collisions at Sea (COLREG) costs too much. In this paper, a negotiation framework is put forward to enable vessels to negotiate to optimize collision avoidance in the COLREG-HIGH-COST situations at open sea. With the framework proposed in this paper, two vessels involved in a COLREG-HIGH-COST situation can negotiate with each other to get a more economic overall collision-avoidance plan than that suggested by the legacy collision-avoidance systems alone.

Summary. In this reference, the authors propose a framework to facilitate economic collision avoidance maneuvers that are proportionately shared between two vessels. These collision avoidance maneuvers are designed with a primary objective of avoiding collisions by a minimum safe distance defined by the give way vessel, and in doing so, executing the maneuvers that are mutually agreed upon in such a manner that economically benefits both vessels, proportionately. The authors propose that this negotiation and execution between vessels is possible through automation, relying on real-time information exchange using AIS. The authors review the development of the collision-avoidance plan and its cost model, which is the starting point for course negotiations between vessels. To execute the actual negotiation, the give-way vessel utilizes preference models that capture: (a) negotiation intentions, which defines the likelihood of negotiation given differences in tonnage between the vessels; (b) negotiation strategy, which defines the percentage of collision risk the give-way vessel intends to eliminate on its initial proposal; and (c) collision-risk tolerance, which defines the minimum safe distance the give-way vessel is willing to accept. Similarly, the stand-on vessel utilizes preference models that capture: (a) action preference, similar to the negotiation strategy for the give-way vessel; (b) risk tolerance; and (c) benevolence, where the stand-on vessel identifies the degree of benevolence the stand-on vessel is willing to incur given the relative size of the give-way vessel. Larger give-way vessels warrant more benevolence, smaller vessels warrant less. The details of each of these models and the reasoning mechanism for execution is beyond the scope of this study, but the principles of their functions are important.

In simulation testing, the authors demonstrate successful negotiation executions between two vessels for the three meeting scenarios at sea – head-on, crossing and overtaking. The authors review the head-on simulation in detail, which presents two vessels approaching on reciprocal bearings with each vessel off the starboard bow of the other. By COLREGs, this would incur a maneuver to starboard of at least 30-degrees by each vessel to safely execute a port-to-port passage. Using the preference models and negotiation framework, both vessels are able to negotiate a smaller course change to port, affecting a starboard-to-starboard passage that meets prescribed minimum safe distance, minimizing the economic impact and avoiding collision. The authors conclude that the proposed framework enables vessels to make more harmonious and economic maneuvers than legacy collision avoidance systems recommend. The authors acknowledge that further development in the collision-avoidance plan is needed, with additional factors accounted for in the future to include next way point and the projected course change at that point.

This source is relevant to this study because it demonstrates the ability to utilize AIS information to proportionately share collision avoidance maneuvers between vessels, which can then be incorporated in future navigation system designs that feature automation of ship control systems.

Marine Electronic Navigation Systems

Giannakopoulos, T., Vetsikas, I. A., Koromila, I., Karkaletsis, V., & Perantonis, S. (2014). AMINESS: A platform for environmentally safe shipping. Proceedings from *PETRA '14: The 7th International Conference on Pervasive Technologies Related to Assistive Environments* (Article 45). Rhodes, Greece: Association for Machine Computing. https://doi.org/10.1145/2674396.2674464

Abstract. Reducing the possibility of ship accidents in the Aegean Sea is important to all economic, environmental, and cultural sectors of Greece. Despite the increased traffic and the related obvious risk, there are currently no national-level monitoring policies in Greece. To this end, we develop the AMINESS platform that will integrate information from multiple sources (e.g. real-time vessel movements, weather data, traffic patterns, information on type and cargo of vessels, environmental data etc.) as well as historical maritime data. This platform offers a web portal accessible by ship owners, policy makers and the scientific community, which can be used to (a) suggest vessel and environmentally optimal safe route planning, considering both the risk as well as the cost (in fuel and time) of the alternative routes, (b) deliver real-time alerts for ships (e.g. danger of collision or capsizing, suspicious/illegal behaviour of vessels), and (c) support policy recommendations both by analyzing statistics and patterns as well as by simulating the impact of different policies. Through these services, the platform aims directly to reduce the risk of a ship accident and consequently to contribute in the safety, management and monitoring of the sea environment and the Aegean Sea in particular. In this paper, we present our ongoing research and development of the AMINESS platform. In particular, we start by presenting the project's general architectural scheme and then the specifications and characteristics of the individual components and modules that make up this system. We particularly focus on some components, especially on the tools that fuse and process the information providing the optimal routing, the alerting and the policy recommendation outputs of the system.

Summary. In this article, the authors propose the establishment of a monitoring system that is able to provide optimal safe routes, deliver real-time alerts to users when there is an increased possibility of an accident, and provide information in support of policy recommendations. These functionalities will be provided by a system called AMINESS, which will integrate information from multiple sources like real-time vessel movements, weather data, traffic patterns, vessel type and cargo data, and environmental data. These data sources are divided into three general categories: (a) the main database, which stores the static and dynamic marine data, geographic elements and weather, (b) the historical database, which stores dynamic vessel data like ship trajectories, and (c) real-time streams of ship positions. Using the data sources, the AMINESS platform will rely on several modules to provide users the desired functionalities. These modules will process the marine data, conduct the risk assessments, determine the risk reduction, and provide a web-based portal for user interaction to access the desired outputs.

The most developed tool in the AMINESS platform is the Optimal Routing Tool, which plots optimal shipping routes to minimize the cost of both time and fuel and the risk. Route optimization is developed using a grid system overlaying the map of the Aegean Sea where routes can be determined from node to node in 16 different directions, carefully balancing risk in the process. In addition, the tool will be able to evaluate historical data by extracting information on dangerous areas and locations where accidents are more probable and find vessels with a history of accidents and non-compliance with rules and regulations. A second tool, the Real-time Alerting tool, will detect events like violations by vessels, which can be reported to authorities or shipping company owners; when a high probability of an accident exists, which can be reported to the vessel(s) in question, authorities, owners and the coast guard; and any other events that present a risk to the vessel like floating debris. The third tool is a policy recommendation support tool which can extract information on shipping to inform users who develop/manage policy. The authors conclude that the AMINESS platform can improve ship safety, management and monitoring of the Aegean Sea environment.

This source is relevant to this study because the route optimization tool can be readily applied to current and future navigation systems for voyage planning, allowing mariners to lay out courses that are optimized for time and fuel while minimizing risk.

Grech, M. R. & Lutzhoft, M. (2016). Challenges and opportunities in user centric shipping: Developing a human centred design approach for navigation systems. Proceedings from OzCHI '16: *The 28th Australian Conference on Computer-Human Interaction* (pp. 96-104). New York, NY: Association for Machine Computing. https://doi.org/10.1145/3010915.3010920

Abstract. Out-of-the-loop, clumsy automation, radar assisted collisions and design induced errors, are all too familiar terms in the human factors literature. Unfortunately, these latent factors are very much present in the operation of maritime navigation systems (Rowley et al., 2006) in some cases leading to unsafe acts with consequential outcomes. Lacking in usability some of these navigation systems have trapped the crew into what is sometimes referred to, but seldom investigated, as design induced errors. This paper will describe the process adopted by the international community with major input from Australia in ensuring that a research driven Human Centred Design (HCD) approach is applied in the development of future navigation systems, resulting in a dedicated guideline. Apart from describing the core elements of the new guideline, the challenges posed from a maritime regulatory perspective in developing and ensuring acceptance will also be discussed.

Summary. In this article, the authors propose implementing Human Centered Design (HCD) as a cornerstone in the development of future e-Navigation systems to improve usability and marine safety. Fundamental to the problem the authors address is the degree of loss of situational awareness, which is becoming more prevalent with more sophisticated technology being introduced into vessels today. The authors cite literature that reinforces various facets of this loss of situational awareness, including a lack of system understanding, improper use of system automation, and poor system design – all examples of design-induced errors.

The authors review the advances made in identifying needs and establishing standards for incorporating HCD into e-Navigation systems. A 2011 gap analysis identified key human factors that navigation systems were facing. These factors include equipment with ergonomic problems because the equipment lacks intuitive human-machine interfaces, poor equipment layout, lack of harmonized symbology for navigation information, lack of key information on displays, inconsistent application of performance standards/guidelines, lack of usability guidelines, lack of standardization of operation of functions, and difficulty in accessing information.

From 2006 to 2013, multiple work groups met to advance the establishment of HCD as a standardized solution for future e-navigation systems that addresses usability issues and improves situational awareness. These work groups produced an initial draft HCD framework to improve usability in e-navigation. The framework includes the design attributes for e-navigation that are established to ensure adherence to the International Organization for Standardization (ISO) 9421-210, Ergonomics of human-system interaction. For future e-navigation system designs, a five-stage development process has been established. The stages include concept development, planning and analysis, design, integration and testing, and operational. The first four stages include embedded HCD activities to: (a) understand and specify the context use, (b) specify user requirements, (c) produce design solutions to meet user requirements, and (d) evaluate the designs against usability criteria. The authors conclude that incorporating HCD, which has received little attention in the maritime domain, in e-navigation should lead to improvements in user effectiveness and increased safety at sea. System designs should support use in low stress and high stress environments.

This source is relevant to this study because it identifies the need for HCD solutions to be incorporated into future e-navigation systems, noting that the lack of HCD solutions in current navigation systems degrades situational awareness. Several points highlighted in this source reinforce lessons learned during the U.S. Navy collisions in 2017 (United States Fleet Forces Command, 2017).

Koromila, I., Nivolianitou, Z., & Giannakopoulos, T. (2014). Bayesian network to predict environmental risk of a possible ship accident. Proceedings from *PETRA '14: The 7th International Conference on Pervasive Technologies Related to Assistive Environments* (Article 44). Rhodes, Greece: Association for Computing Machinery. https://doi.org/10.1145/2674396.2674463

Abstract. The goal of the AMINESS project is to promote shipping safety in the Aegean Sea though a web portal offering different levels of access to relevant stakeholders such as ship owners, policy makers, the scientific community and the general public. The portal will have three principle uses. The first is to suggest both vessel and environmentally optimal safe route planning for ships. The second is to produce alerts for ships in real time with respect to potential hazards associated to other ships, as a function of its location and planned route, its cargo and the meteorological/sea conditions. Finally, the third is to support policy recommendations, through analysis of historical data in short and long term periods that correlate safety with ship trajectories. To that end, the risk of a possible accident occurrence in the Aegean Sea is being calculated using Bayesian networks (BN). Two types of accident scenarios (collision and

grounding) have been studied. A simplified Bayesian model has been developed to predict the risk of an accident given the main characteristics of the vessel, namely the ship type, size, age and flag, which are inputted to the present model. The appropriate input data has been provided by the AIS (Automatic Identification System) sign us with. Training of the developed Bayesian network was performed using the data of both the historical accident database of Marine Rescue Coordination Center and the AIS and some use cases in the area of Aegean Sea is presented in this paper.

Summary. The authors utilize a Bayesian network to predict the risk of a possible ship accident utilizing vessel static parameters. The authors chose a Bayesian network as it enables a graphical representation of causal relations between different parameters, demonstrated by a set of nodes representing random variables. The model reveals explicitly the probabilistic dependence between the set of variables displayed via a directed graph. In a simple use case, the Bayesian model is then used to calculate the risk of collision or grounding using the inputs of ship type, age, flag and size. Applying the network for one month (August 2009) of sea trajectory data from the Aegean Sea, the risk of the respective ship is calculated. By displaying the results in a spatial distribution, color-map, the risk to the environment can be conveyed. The authors validate the results are v using accident data from 2008 to 2012. The authors conclude that a simple Bayesian network can be used to quantify risk for vessels with static parameters.

This source is relevant to this study because it validates methodologies exist that can quantify risk for vessels for multiple purposes; in the case of this source, the risk to the environment. Alternatively, similar methodologies can be used to identify vessels that are at higher risk of collision and thus prioritize implementation of advanced navigation systems with improved collision avoidance algorithms, assignment of more experienced mariners to mitigate risk to those platforms, and use of additional algorithm factors like minimum safe distance to increase margin to safety

Pietrzykowski, Z., Wołejsza, P., & Borkowski, P. (2017). Decision support in collision situations at sea. *The Journal of Navigation*, *70*(3), 447–464. https://doi.org/10.1017/S0373463316000746

Abstract. The known navigational systems in use perform information functions and as such are helpful in the process of safe conduct of a vessel. One of the ways to assist in reducing the number of marine accidents is the development of systems which perform decision support functions, i.e. automatically generate solutions to collision situations. The use of information (and communication) technologies including knowledge engineering allows the generation of proposals for anti-collision manoeuvres taking into account the COLREGs. Demand for further enhancement of navigational safety by limiting human errors has initiated a trend to convert navigational information systems into decision support systems. The implementation of decision support systems will potentially reduce the number of human errors, which translates into a reduction of accidents at sea and their adverse consequences. This paper presents a summary of the research to date on the navigational decision support system NAVDEC. The system has been positively verified in laboratory conditions and in field tests – on a motor ferry and a sailing ship. Challenges associated with the development and implementation of such systems are outlined.

Summary. The authors evaluate the utility of a navigation decision support system to reduce the impact of human errors on maritime accidents. This article focuses on the development and utility of information systems to support the decision-making process using NAVDEC, a navigational decision support system, as the framework. The authors highlight challenges for maritime decision-making using current technology and how these challenges can be overcome with decision support systems to address one of the main causes of accidents at sea – human error. Current challenges include navigational systems in use today relying on data processing, thus limiting their performance to mostly information functions that limit access to ready solutions to collision situations relative to all vessels in the vicinity of a ship. By building on the e-navigation concept, defined as "the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth-to-berth navigation and related services for safety and security at sea and protection of the marine environment" (p. 451), the authors discuss the critical requirements for communications standards to ensure decision support systems' analysis and interpretation are accurate. Key requirements for these standards include the ability to deliver appropriate information ship-to-ship, ship-to-shore, shore-to-ship, and shore-to-shore, regardless of the number and scope of the information or type of navigation system used; and the need for unequivocal interpretation of the navigational information.

The authors provide accident frequency and cost implications to the maritime industry using current information-only navigation systems to set the context for the need for decision support systems. To address this challenge, the authors use NAVDEC as the example decision support system to demonstrate its advantages to mariners. The authors present limitations and results from NAVDEC testing, which included simulation studies in an area free of navigational dangers in four different scenarios and testing on *MV*

Hammonia Berolina sailing on a fixed route from Algeciras in Spain to several West African ports. Limitations include not taking into account relationships between other vessels, thus there is no accounting for actions that might be taken between two other ships relative to each other; time limits to generate a solution; and not creating relevant databases. Results of the NAVDEC testing include correct calculations of CPA and time to CPA (TCPA); correct calculations of new, safe courses at the designated distance of one nautical mile (NM);correct display of the recommended trajectory; and correct calculation of sectors for recommended courses for at least 40 vessels in a pre-defined five-second time period.

The authors present basic functionalities of NAVDEC, using as an example the collision between *MV Gotland Carolina* and *MV Conti Harmony*, which occurred on 19 April 2008. Examples of basic functionality include determination of the parameters of the encounter, generation of anti-collision maneuvers including speed changes, and display of a proposed safe trajectory for own ship. The authors conclude that navigation decision support systems, which are shown to reduce human error, should be included in future e-navigation systems. However, based on the complexity of such systems, additional experience and defined guidelines are required to accelerate what will be a time-intensive effort of implementation.

This source is relevant for this study because it effectively demonstrates the advantage a decision support system can provide mariners for collision avoidance. While the NAVDEC displays are rudimentary, experienced mariners can interpret the analysis provided by NAVDEC to improve in-situ decision-making.

Conclusion

The growing global economy has resulted in steady and continual growth in the maritime shipping industry (Allianz, 2017). This growth has driven commercial carriers to build more and larger ships to meet the increasing demand of the commercial maritime industry (Allianz, 2017; International Chamber of Shipping, 2017; United Nations, 2017). As a result, the risk to mariners of being involved in a marine accident has increased (Allianz, 2018). When a marine accident occurs, it is more likely to be severe and to incur significant losses in terms of cost and, potentially, life; the U.S. Navy collisions in 2017 are examples of both types of loss (Allianz, 2108; Department of the Navy, n.d.). Marine accidents continue to occur despite advances in technology which have given mariners improved navigation systems and better situational awareness of the marine environment around them (Allianz 2018; Lei et al., 2018; Schroder-Hinrichs et al., 2012; United States Fleet Forces Command, 2017).

This annotated bibliography presents sources that address the research question of how shipboard, integrated navigation systems can better display collision avoidance maneuvers to reduce the risk of collision. Key findings are presented below in the categories of mariner decision-making, collision avoidance and marine navigation systems.

Mariner Decision-making

In 2017, the U.S. Navy experienced three collisions at sea (United States Fleet Forces Command, 2017). Investigations into two of these three collisions conducted by the Department of the Navy (n.d.) identify several factors that contributed to the collisions, including failure to plan for safety, adhere to sound navigation practices, use available navigation tools, adhere to COLREGs, and respond effectively when in extremis. All of these factors are attributable to human error (Department of the Navy, n.d.). Extensive research has been conducted to identify causal factors for maritime accidents (Department of the Navy, n.d.; Erol et al., 2017; Grech et al., 2016; Schroder-Hinrichs et al., 2012; Weng et al., 2018). The research of Mohovic et al. (2016) shows that incorrect application of COLREGs is one of the most prevalent causes for collisions at sea. Similarly, when evaluating contributing organizational factors other than human error, Schroder-Hinrichs et al. (2012) identify six additional factors that have generally contributed to marine accidents since the loss of the Titanic in 1912. These factors include authority gradient, or the distribution of decision-making and the balance – or imbalance – of authority and power in a group or organization and the resulting influence on communications; group think; cognitive hysteresis, or resistance to revising a situation assessment; unanticipated consequences of new technology; organizational influences and efficiency-thoroughness trade-off, or balancing the time and measures to ensure safety operations with economic considerations (Schroder-Hinrichs et al. 2012). Five of these six factors, the lone exception being efficiency-thoroughness trade-off, were present to some degree in the collisions investigated by the U.S. Navy in 2017 (Department of the Navy, n.d.). Analysis by Weng et al. (2018) confirms human error as the most prevalent cause of marine accidents, but also identifies additional non-human factors that affect collision severity including operational conditions like visibility, location, and time.

With a thorough understanding of factors that contribute to collisions, electronic navigation systems designers and manufacturers can mitigate their impact by incorporating current research initiatives into future designs (Grech et al., 2016). For example, by knowing the non-human collision factors identified by Weng et al. (2018), electronic navigation system designs can incorporate increased margins to improve safety. Examples might include automatic notifications for reductions in speed when approaching a location with higher risks for collision or when degrading weather is encountered (Erol et al., 2017). Similarly, future displays can be modified to display vessel behavior to improve situational awareness and mariner response (Jin et al., 2018). Taking that concept a step further, displays can be modified to mitigate the impact of organizational factors that affect collisions (Schroder-Hinrichs et al., 2012). Examples include two-party acknowledgement of a pending collision to mitigate group think and color-coded hierarchies for course recommendations to prioritize safety over economics to mitigate efficiency-thoroughness trade-offs (Schroder-Hinrichs et al., 2012).

Collision Avoidance

Current technology exists in electronic systems today that allows for the recognition of a risk of collision (Fang et al., 2017; Grech et al., 2016; Lisowski, 2013). As defined by the International Maritime Organization (2003), a risk of collision exists when another ship exhibits a continual reduction in range, or distance, with no appreciable change in bearing. In single-ship encounters, under optimum conditions with calm weather and unlimited visibility, it is a relatively simple matter for mariners to handle this potential encounter (Lisowski, 2013). This encounter rapidly becomes more complex when multiple ships are operating in proximity to own ship, visibility is restricted, and/or weather is degraded (Lisowski, 2013). Leveraging technology to facilitate early recognition of a risk of collision would increase margins to safety by assisting mariners in their decision-making (Lisowski, 2013).

As Boubeta-Puig et al. (2012) highlight, mariners have the ability to leverage current technology to facilitate recognition of a risk of collision. Current information systems like the Automatic Identification System (AIS), a system based on a service-oriented architecture that combines complex event processing and a data distribution system could be used to trigger alerts to marine users (Boubeta-Puig et al., 2012). Theoretically, thresholds could be established that would provide audible and visual alerts, improving the usability of future systems for mariners and reducing the risk of collision (Grech et al., 2016). Taking this scenario a step further, if factors and parameters associated with a risk of collision can be used to identify a risk of collision, then it follows that those same factors and parameters can be managed dynamically to further increase margins to safety (Erol et al., 2017; Giannakopoulos et al., 2014; Grech et al., 2016).

Erol et al. (2017) identify through their research several parameters that are directly proportional to the severity of a marine accident like a collision. Ship length overall (LOA) and weather are two examples of these types of parameters (Erol et al., 2017). Thus, as weather degrades or the size of the other vessel increases, electronic navigation systems could dynamically increase previous collision detection thresholds by increasing minimum acceptable contact range threshold, which would then differentiate between high-risk and low-risk encounters (Koromila et al., 2014). The result of adjusting these thresholds is that mariners become more readily aware of collision risk, which would be warranted when optimum conditions are not prevalent (Koromila et al., 2014).

Extremis situations could be avoided by leveraging mariner behavior in encounter scenarios at ranges well in excess of when COLREGs typically applies, particularly when such mariner behavior is not consistent with guidance published in COLREGs but is nonetheless optimized (Lei et al., 2018). Should a ship find itself in extremis and collision avoidance becomes necessary, the research of Fang et al. (2017) shows that optimal collision avoidance maneuvers specific to the maneuvering vessel by accounting for advance and transfer of that ship can be determined and communicated to the vessel master. This analysis has been shown to be successful for both single-ship and multi-ship scenarios (Fang et al., 2017). An even more advanced, burden-sharing algorithm is presented by Qinyou et al. (2006), who propose sharing contact avoidance maneuvers between vessels proportionate to the relative size of the vessels, to minimize cost through optimum maneuvers of both vessels involved. As Lisowski's (2013) research using optimal and game control algorithms shows, optimal maneuver analysis for both extremis and non-extremis collision avoidance scenarios can be extended to high contact density scenarios.

Marine Electronic Navigation Systems

Regardless of the algorithms employed to identify risk and optimize maneuvers, the electronic navigation systems of the future need to incorporate human-centered design to enhance situational awareness for mariners (Grech et al., 2016). Systems in use today are too clumsy, lack usability, degrade situational awareness and make mariners susceptible to design-induced errors (Grech et al., 2016). By leveraging multiple information streams, electronic navigation systems can provide improved utility to mariners to reduce the risk of collision, even as early as the voyage planning phase (Giannakopoulos et al., 2014). Graphical displays of bad weather, congested traffic patterns, predominance of vessel types and other environmental data can assist mariners in planning optimized voyage routes to minimize time and fuel consumption while minimizing risk (Giannakopoulos et al., 2014). This capability has been successfully demonstrated through the AMINESS platform utilized in the Aegean Sea maritime operations (Giannakopoulos et al., 2014).

As previously discussed, human error remains one of the most prevalent causal factors for collision (Grech et al. 2016; Mohovic et al., 2016; Pietrzykowski et al., 2017; Schroder et al., 2012; Weng et al., 2018). In extremis scenarios, navigation system displays can be modified to provide mariners with the optimal course maneuver to avoid a collision during extremis situations (Pietrzykowski et al., 2017). Pietrzykowski et al. (2017) successfully utilized a decision support system, NAVDEC, to display correct and timely collision avoidance maneuvers in extremis. This functionality would have undoubtedly assisted the mariners involved in the *USS Fitzgerald* collision, where indecision and conflicting orders in extremis contributed to the collision with *M/V ACX Crystal* (Department of the Navy, n.d.). Additional enhancements to visual representation and algorithm modifications can be made to capture the quantification of risk based on vessel type, which has already been utilized effectively (Koromila et al., 2014). Using a Bayesian network to predict the risk of a possible collision, navigation displays can be enhanced to identify vessels that display a high degree of risk, based on the vessel's historical performance, type of cargo carried, or other relevant factors (Koromila et al., 2014). Once identified, modifications to collision avoidance algorithms can be made, optimal collision avoidance maneuvers can be taken, and algorithm thresholds can be set to increase margins to safety and reduce the risk of collision.

Concluding Remarks

There is ample evidence that confirms human error remains one of the most prevalent causes of maritime accidents (Grech et al. 2016; Mohovic et al., 2016; Pietrzykowski et al., 2017; Schroder et al., 2012; Weng et al., 2018), despite advances in technology that have given mariners more information on their environment and the ships they are operating in proximity to than they have ever had at any time in history (Allianz, 2017; Allianz 2018; Lei et al., 2018; Pietrzykowski et al., 2017; Schroder-Hinrichs et al., 2012; United States Fleet Forces Command, 2017). Poor designs in current electronic navigation systems are contributing to the risk of collision caused by human error (Grech et al., 2016). Research shows that electronic navigation system designs can be improved by incorporating better collision avoidance algorithms and human-centered design focus and by developing enhancements to mitigate factors known to contribute to maritime accidents (Department of the Navy, n.d.; Erol et al., 2017; Grech et al., 2016; Lisowski, 2013; Qinyou et al., 2006; Schroder-Hinrichs et al., 2012; Weng et al., 2018). By successfully incorporating these elements into future systems, the risk of marine accidents at sea can be reduced, improving safety while minimizing the operational, economic, and environmental impact that collisions at sea incur for both the U.S. Navy and the maritime industry (Giannakopoulos et al., 2014; Grech et al., 2016; Koromila et al., 2014).

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