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Abstract

The continuing losses of vessels and the ever increasing volume of cargo carried by ship marks marine traffic as a high risk activity where a single accident has the potential to incur large human, environmental and economic losses. Collision and grounding contributes a significant portion of the total number of accidents at sea and are a manifestation of the fundamental situation where by vessels are at the wrong place at the wrong time. In order to quantify the probability of these unfortunate events one can turn to either observation or simulation, but observation has previously been limited by the difficulties in observing ship traffic, while simulations with bridge simulators are time consuming and expensive.

The Automatic Identification System (AIS) for ships was introduced as an real-time monitoring system which would augment ship-borne radar and monitoring by Vessel Traffic Services, but may also be used as an convenient method of observation of ship traffic with position and speed measurements from uniquely identified ships. The data available form the system can then be used to estimate the probability of a vessel being in the wrong place at the wrong time if a method to analyze the data is available. This thesis presents a method to process the raw AIS data into a format which both eases analysis and allows for a fine grained analysis of traffic patterns. The method can be used to:

1. Detect regional traffic patterns
2. Collect AIS sample into per voyage time-series and attach the time-series to a traffic pattern
3. Analyze the traffic patterns and generate an approximate simplified navigational plan which can be connected to the navigational markers in the area

The use of observed data can be used to estimate the probability of accidents or dangerous situations occurring during normal operation, but simulations continue to be the preferred tool to represent out-of-the-ordinary scenarios. The human element, be it operation or design, are identified as the root cause of the majority of incidents and accidents. The use of human-in-the-loop simulations has secured the relevance of simulation as a tool for risk analysis of maritime traffic, but the resource requirements and constraints of the human operator has limited the application of simulation. This thesis presents a simulation model intended for use in autonomous and efficient time-domain simulations which can be used on regular workstations in order to undertake preliminary simulation studies of marine traffic to either deliver estimates or as a screening procedure before undertaking the more expensive simulations with a human operator.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of philosophiae doctor.

This doctoral work has been performed at the Department of Marine Technology, NTNU, Trondheim, with Torgeir Moan as supervisor.

This thesis is a part of the ScenaRisC&G research project at the Department of Marine Technology financed by the Norwegian Research Council.

Acknowledgements

The author wishes to acknowledge the support of the Department of Marine Technology at the Norwegian University of Science and Technology where the majority of the work was carried out with support from the Research Council of Norway (RCN) and the Centre for Ships and Ocean Structures.

I also wish to thank my supervisor Professor Torgier Moan for valuable discussions and input about the thesis and research in general, the head of the RCN project ScenaRisC&G project Professor Jørgen Amdahl for giving me the opportunity to pursue a PhD and Dr. Petter Friis-Hansen for introducing me to the Automatic Identification System. I also wish to thank friends, colleagues, former and present PhD students both at the Marine Technology Centre at Tyholt and elsewhere for support and discussions.

Finally I would like to thank my girlfriend Tanja for everything.

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Chapter 1

Introduction

1.1 Background

The oceans have always been closely related to human civilization, the development of trade, exploitation and exploration by ship has continued from the first time the Minoans navigated after the stars, the sea-born raids and invasion of the British isles by the Vikings to the success of the Dutch trading companies and the rise of imperial Britain. Access to the sea as a trade route has maintained empires and enabled charting and exploration of the world by sea in search of new opportunities for trade. The prospect of shorter and more efficient trade-routes have resulted in canal networks, the accidental "discovery" of the Americas by the Europeans and even bridges between oceans in the form of the Panama and Suez canals.

While the world seems like a much smaller place in the age of world-wide communication networks, satellite navigation and closely intertwined economies, sea-trade has never lost its position as the worlds preferred and most effective means of transportation carrying everything from finished goods to raw materials. The volume of ship borne cargo has increased, although not totally immune to recession, steadily in the last 50 years as seen in Figure 1.1.1. From Figure 1.1.1 it is evident that the cargo volume of the merchant marines of the world is largely used for the transportation of raw-materials such as iron ore and hydrocarbons. The number of vessels in the world fleet was approximately 87 000 in 1999 (Guedes Soares and Teixeria, 2001) and the total tonnage has continued to increase.

Transportation by ship is associated with a "risk" originating from the uncertain outcomes should the vessel be damaged or lost. "Risk" is an ambiguous term, but most definitions agree that the term is an aggregation of frequency and consequence such as injuries and loss of life and the environmental and economic impact. Ships as a transportation system is subject to a continuous sequence of events particularly during navigation (path-finding) and maneuvering (execution). Repetition of errors during navigation and maneuvering in confined waters will eventually lead to collisions or grounding, which makes a sizable contribution to the overall number of accidents in the world fleet (Antãno and Guedes Soares, 2008; Guedes Soares and Teixeria, 2001; Kristiansen, 2005). There is little room for error in confined waters and an grounding accident can have a large and visible impact on the environment. The most notorious example of a ship accident with enormous environmental and economic impact is the grounding of the Exxon Valdez.

Table 1.1: Oil spills from recent ship accidents in Norway with a high media profile

Name	**Ship type**	**Oil discharge**
Full City	Bulk carrier	300 tones
Server	Bulk Carrier	200 tones
Rocknes	Bulk carrier	300 tones
Green Aalesund	Refrigerated cargo ship	460 tones
John R	Bulk Carrier	200 tones

The severity of accidents involving crude carriers can be seen in Figure 1.1.2 which shows the total oil spills from tankers where it is evident that the total amount of oil spilled has decreased significantly form the levels of the 1970, but also that individual accidents can discharge significant amounts of oil. The Exxon Valdez accident is listed with 40 000 tones discharge as one of the larger, but not largest, spill and serves as a warning that a single accident can have disastrous consequences. Accidents with equal and even larger oil spills has occurred, but the Exxon Valdez accident has formed the public perception of risk and established the large scale release of oil or other hazardous substance as a possible consequence. Due to the cargo capacity of a ship, sea transportation can be defined as a high risk activity. The Exxon Valdez accident has its root cause in organizational and human factors which ultimately led to erroneous navigation of the vessel and subsequent rupture of the cargo tanks. The attention generated by the accident has not resulted in an elimination of accidents due to erroneous navigation, as these accidents continue to occur even in the age of global positioning system, electronic chart displays and voyage planning systems. This can be expected as the main element in the accident was human factors which are identified as a root cause of up-to 90% of accidents (Hollnagel, 1996). While the high profile international accidents are tanker accidents with cargo discharge, the environmental impact of fuel oil discharge can be significant in the immediate vicinity of the accident site. The high profile ship accidents in Norway during the period 1999-2009 all involve cargo or bulk carriers with resulting spills of fuel oil. Accidents which share the traits erroneous maneuvering and navigation with the Exxon Valdez continue to occur such as two recent accidents in Norway which both occurred during pilotage: the “Federal Kivalina” (2008) and the “Crete Cement” (2008).

Federal Kavalina The Federal Kavalina, a 200m bulk carrier, was chartered to transport a cargo of aluminum oxide from Vila Do Conde in Brazil to the Norwegian port of Karmøy with Sunndalsøra as alternate destination. The ship departed Vila Do Conde at the 18. of September 2008 and was redirected to Sunndalsøra on the 22. of September.

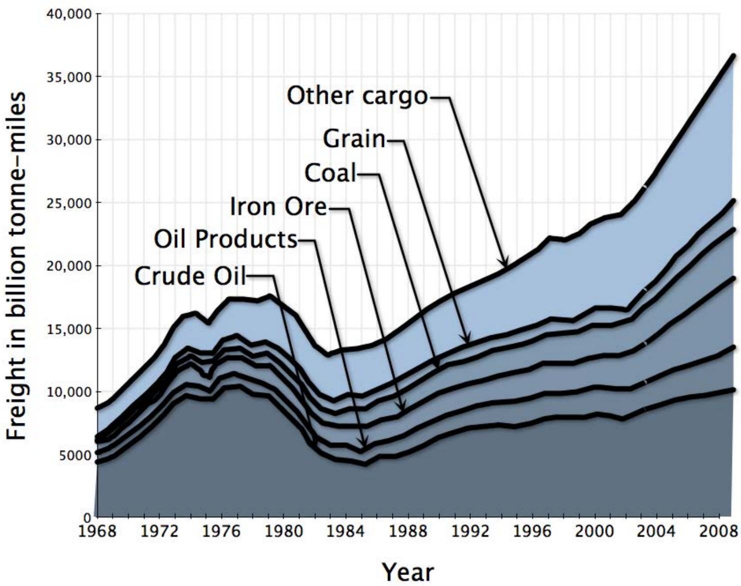


Figure 1.1.1: The evolution of cargo and travel distance of the global fleet. The global fleet is heavily used to move iron ore and hydrocarbons around the globe. Statistics published by International Chamber of Shipping (Internarional Chamber of Shipping, 2010) based on source material from Fearnley's Review.

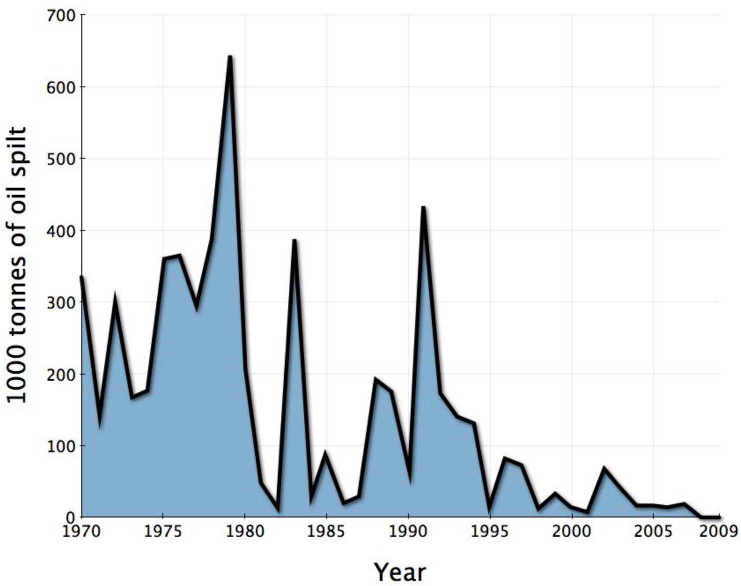


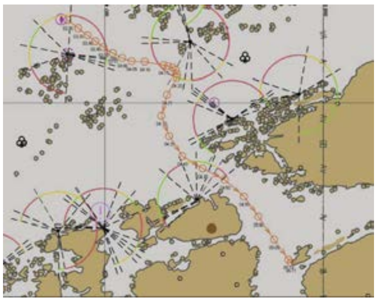
Figure 1.1.2: Total amount of oil spilt in discharges exceeding 7 tones as published by the International Tanker Owners Pollution Federation Limited (ITOPF, 2010).

The ship management company required quay-to-quay plans to be present before departure, but the vessel did not possess the required charts of the approach to Sunndalsøra. The vessel requested electronic chart codes for the approach to Sunndalsøra which was ordered by the management company at the 23. of September and delivered to the ship by email within 24 hours. The management company and local agent arranged for the proper paper charts to be delivered by the pilot prior to the final approach. The crew undertook two unsuccessful attempts at activating the required electronic charts, and notified the management company of the problems, which in turn advised the vessel to proceed as planned as the required paper charts would be delivered by the pilot. The pilot delivered the paper charts upon arrival, but the crew failed to plan a passage to Sunndalsøra. During the approach to Sunndalsøra the pilot became occupied with weather reports and quay restrictions, while the master devoted time to resolve a technical issue with the ships AIS. The pilot ordered the ship to steer towards a beacon on Skarvbergneset, and the vessel proceeded in confined waters without a passage plan. The bridge crew, including the pilot, failed to order a change of course in due time. The vessel ran aground on Skarvbergneset, 45 seconds after the crew became aware that they were dangerously close to land.

Crete Cement The Crete Cement was carrying 5000 tones of cement bound for Slemmstad when it ran aground at Aspond in the Oslo-fjord. The vessel continued towards Slemmstad, but when it was discovered that the vessel was quickly taking in water, the course was changed and the vessel was intentionally beached at a designated area. The crew was evacuated and the vessel settled on the shallow sea-bed. Oil leaking from the vessel resulted in a local oil spill which was contained. The vessel was under pilotage and the pilot was present at the bridge when the grounding occurred. The voyage was considered routine by both the pilot and crew, and the voyage was planned on both paper and electronic charts. The navigational markers in the area had undergone reconstruction work recently. The vessel did not have access to the corrections due to the choice of chart supplier and the type of work which led to the crew being unable to confirm their position visually. The pilot was familiar with the changes and maneuvered the vessel by manipulating the course auto pilot without interaction with the officer on watch. Due to a lapse in attention from the pilot the vessel continued without changing course at the appropriate time, the vessel continued on the same course until the GPS signaled that the way-point was reached. The helmsman brought this to the attention of the pilot some 30-40 seconds after the GPS alert. The helm was ordered hard to starboard, but the vessel ran aground mere seconds after it began to change course.

1.2 Analysis of accidents

Two distinct types of analysis, “retrospective” and “predictive” are used to either quantify the probability of errors and malfunctions during design or to formalize the experiences of past accidents into safety advise. An accident can not be observed without context as it is the perception of the observer which determines if a system state is indeed an accident.



(a) The path of the "Federal Kavalina" prior to running aground where the ships heading towards Skarvbergneset was left unchanged

(b) The "Federal Kavalina" aground at Skarvbergneset with cargo holds and fuel tanks intact

(c) Extensive damage to the bow of the "Federal Kavalina" is seen after the vessel entered dry-dock for repairs

Figure 1.1.3: The "Federal Kavalina" grounded and sustained extensive damages to the bottom in the bow section, all images from the Accident Investigation Board of Norway's official report (Accident Investigation Board Norway, 2010)

Figure 1.1.4: The "Crete Cement" purposely beached after grounding and taking in water both fore and aft. Photo from the the Accident Investigation Board of Norways official report (Accident Investigation Board Norway and The Bahamas Maritime Authority, 2010).

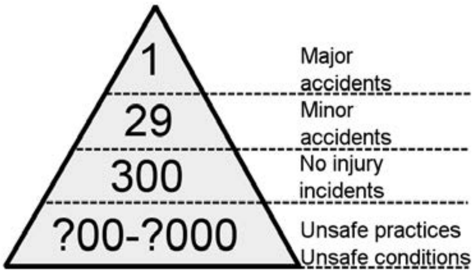


Figure 1.2.1: The ratio between major accidents and underlying unsafe conditions and practices illustrated as a pyramid. The underlying assumption is that incidents and accidents are manifestations of the practices and conditions, and that the number of accidents can be reduced by responding to reports of unsafe and near-miss conditions.

The case of the grounding of the Federal Kavalina is from a purely environmental point of view not an accident but a near miss since it did not involve any release of harmful substances, but from an economic point of view it was clearly an accident as the ship-owner and management incurred significant expenses due to physical damage on the ship and broken contractual obligations. This illustrates accidents as a structure-less phenomenon which needs a firm frame of reference in order to establish the causes, an important part of retrospective analysis is the imposition of a predefined structure and the construction of a causal chain leading to an accident.

Systems have operating instructions and barriers designed to contain deviations before they evolve into full-blown accidents, this leads to a continuum of states which can be classified depending on outcome, there may be little more than a functioning safety barrier which separates an near-miss from an accident. The continuous opportunity of errors and mishaps in the world fleet implies that statistically events evolve into near-miss events and accidents on a regular basis. The statistical relationship between the underlying operational safety level, the continuous stream of events and undesirable outcomes is captured in Heinrichs (Heinrich, 1950) iceberg theory shown in Figure 1.2.1. Heinrichs iceberg theory postulates that undesirable events are a manifestation of the underlying level of safety which implies that this relationship can be exploited in order to increase system safety by recording of the minor events, lapses and near-misses in order to detect any unforeseen causal relationships leading to a combination of events evolve into an accident. The Crete Cement and Federal Kavalina reports are two examples of retrospective accident analysis. Accidents and incidents are analyzed in order to exploit Heinricks iceberg theory to increase system safety and to assign responsibility for insurance or possibly criminal charges. A defining characteristic of retrospective analysis is that an past event is needed before the activity can begin the meticulous dissection of the event sequence. Retrospective analysis can only highlight deficiencies a-posteriori and can only prevent any identified deficiencies in the safety level to repeatedly manifest themselves as incidents or accidents.

1.2.1 Risk analysis

Predictive analysis is often understood as a synonym to risk analysis which is the attempt to quantify the future expected consequences of operation. The term “risk” is a composition of two terms, how likely something is to go wrong and the associated adverse consequences. Risk analysis has evolved from the need and desire to improve the safety of systems a-priori, and not merely respond to the manifestations of underlying unsafe practices. Predictive analysis is the methodical exploration of possible deviations from intended behavior and to assess their causal relationships, consequences and to assign a probability of a “successful” evolution of the causal chain. Predictive analysis can be divided into the following two types

Qualitative Analysis of possible critical conditions and how they emerge

Quantitative Further analysis of the expected frequency of the identified critical conditions

While qualitative analysis answers how events may occur, quantitative risk analysis focus on the frequency of critical conditions and events, and inherits the outcome from a predefined scenario. Risk analysis is an iterative process of identification, evaluation and mitigation as seen in Figure 1.2.3 where qualitative and quantitative analysis serve in complementary roles as scenario definition and quantification. The scenario determines the severity of an undesired event and the quantification is usually a determination of the probability of the ultimate outcome. A traditional method to evaluate this frequency is formal safety assessment (FSA) in combination with fault tree analysis. FSA include rigorous rules for documenting the possible failure scenarios and causal event chains. The frequency of a particular scenario is estimated with a tree of logical gates where the root node is the undesired outcome and the preconditions are represented by the remaining nodes in the three. The probability of a specific sequence of events is extracted from the tree once all the probabilities of the nodes are known. If the probability of an adverse event is found to exceed the tolerance level for the analysis, the event tree can be further analyzed to either find suitable areas of improvement or augmentation to lower the frequency and, implying a lower risk level. Risk analysis is always a trade-of between consequence and frequency in search of the a combination which satisfies the “As low as reasonably practicable” (ALARP) criterion where risk is classified as “unacceptable”, ALARP and “acceptable”. The ALARP criterion is best illustrated by the graph in Figure 1.2.2 where consequence and frequency spans a continuum. The ALARP model is used to determine the effectiveness of risk mitigation measures.

Analysis of ship traffic is centered around estimation of the frequency of accidents, the present state of knowledge and computers do not allow an integrated analysis of both ship dynamics and structural mechanics. Structural analysis is required to make predictions about the consequences on the structural integrity while simulations of ship dynamics can provide accident scenarios and frequency. Predictive analysis of ship is focused on the probability that a vessels track will intersect a safety zone , such as a bridge pier, land or shallows. The classical illustration is the probability distribution of the ships extent super-

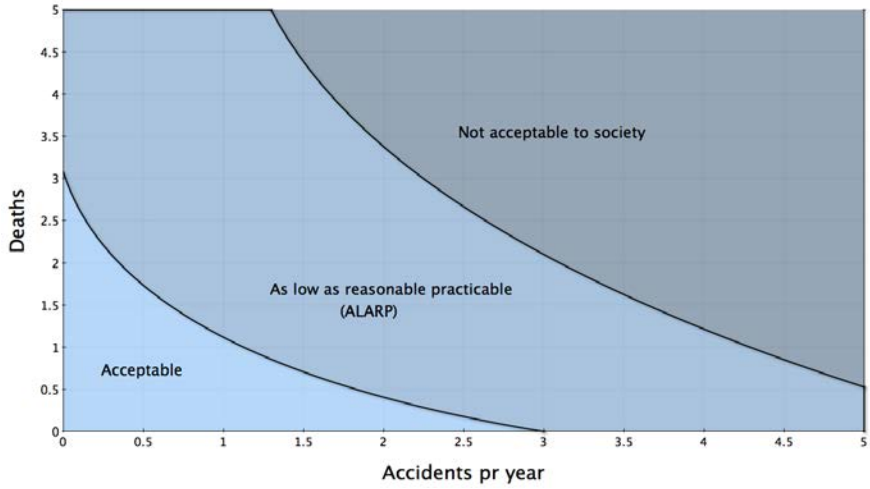


Figure 1.2.2: An illustration of the risk domain with society's conception of the security of the operation superimposed.

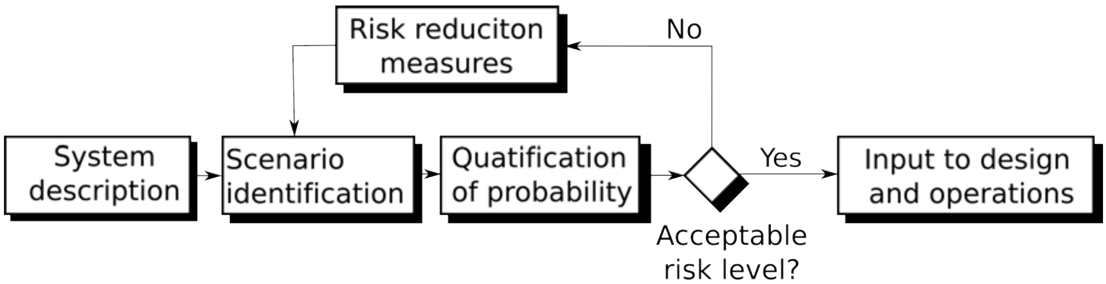


Figure 1.2.3: Risk analysis process with identification, quantification and mitigation as the integral activities

imposed on an ideal track-line as seen in Figure 1.2.4 where the probability of violating the safety zone is represented by the shaded area. The presentation of the probability of safety zone violations is of nefarious simplicity, but to obtain the probability distribution of the vessel position is another matter. Established traffic patterns near existing installations allows the use of observations, but when analyzing changes to the fairway predictions must be made about both ship dynamics, navigation and maneuvering.

1.3 Navigation and maneuvering

Navigation and maneuvering are two processes where the human element contributes directly to the outcome. The planning of voyages and maneuvering in confined waters is a process where the master and helmsman exercise direct control of the ship according to a predefined navigational plan. Voyage planning and execution is distinct stages as operational and regulatory requirements mandate a prepared plan for the voyage. During execution of the planned maneuvers, the master and helmsman make frequent ob-

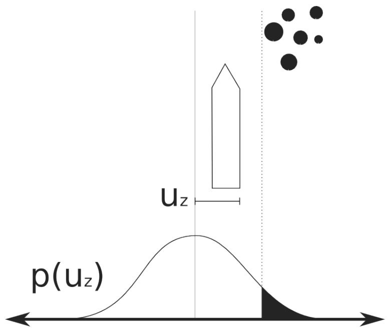


Figure 1.2.4: Probabilistic view of vessel grounding highlighted by the shaded area under the probability density function. The probabilistic density function for the ship side position is problematic in predictive analysis due to its dependence on both ship dynamics and human factors.

servation of the surroundings and takes appropriate actions when needed. The process is almost a blueprint for a general cognitive process which is modeled as consisting of observation/interpretation, planning and execution. Maneuvering of vessels can be seen as a special case of this model of cognition as there is a predefined navigational plan which is formulated in advance, maneuvering is then an iterative process of observation, interpretation and execution in the context of the plan. Controlling a ship is a demanding task as vessels of size has slow dynamics and limited control forces. The slow dynamics does not translate into time for observation and decision as the time-window for correctly timed actions remain small. Training in simulators has long been an integral part of maritime education and maintaining emergency skills where real-time simulations provides an interactive simulation of ship dynamics. Autonomous simulations of the same ship dynamics in fast-time has become a tool for risk-analysis, but without the cognitive capacity of the human operator.

1.3.1 Ship-handling simulations

Simulations in general and time-domain simulations in particular are predictive analysis techniques since a prediction about a systems state at a future time is the output. Time-domain simulations have increased in popularity due to the availability of simulation tools, the ease of expressing models in the time-domain and a continuing increase of computer power accompanied by a decrease in hardware costs. Numeric integration is widely used to simulate the evolution of dynamic systems models formulated as a set of differential equations. Systems can be modeled and simulated in software environments where self-contained system components are available in order to produce a “system of systems” simulation model.

Real-time ship simulators are used for “in the loop” tests of dynamic positioning systems with production hardware and software connected to a time-domain simulator which provide the same interface as a real-world dynamic positioning installation. A more common use of time-domain simulations is training where the simulator provides an interactive virtual environment. Simulators have become an indispensable tool in personnel training and is used to train aircraft pilots, nuclear reactor operators, drilling operators, chief engineers and ship masters. Since training simulators are already adapted for human operators they are also used to test new vessels, channel and fairway designs. Real-time human-in-the-loop simulations require resources both in the form of time, technical facilities and man-hours to operate the simulator and to participate in the simulations. The use of desktop fast-time simulators can be an efficient means of reducing the resources required for human-in-the-loop simulator studies as shown in (Hutchison et al., 2003), but there is little literature which discuss the errors introduced by replacing the human operator. As previously discussed the elimination of the human element and replacing it with a guidance and control system is bound to introduce errors both in interaction and in model structure. The similarity in structure between the real-word counterpart and the model determines if a model is provided, or the component is simply represented by a different component with a similar interface.

1.3.2 Previous work on analysis and applications

The choice of estimation or measurement of the frequency contribution is the major distinction between risk analysis of existing and proposed systems. Heinrichs law can be exploited in the case of existing systems and there should be a focus on collecting actual performance data. Performance data cannot be collected for new or modified systems and predictions based on either first-principles or comparable systems are the only source of real-world data. Observation of ship traffic and maneuvering has traditionally been costly and the independent nature of each vessel has led to a low availability of data for analysis. Simulations have stepped in to filled the gap for maneuvering, but the introduction of the automatic identification system (AIS) brought with it new opportunities for data collection both in scale and in observation method since position reports for any AIS equipped ship can be accessed from a central point and stored for later analysis. AIS has seen wide adoption and applications in real-time monitoring and traffic services but is an under utilized data source for historic analysis. Historic data from ship maneuvering can be used both as a base for analysis of establishing and hugh-level overview and determining trade-routes as seen in (Gucma and Goryczko, 2007; Gucma and Przywarty, 2007) and to derive area traffic densities. The regular sample rates of AIS should allow for a much more detailed analysis of ship traffic, down to the maneuver level. The relationship between the data form AIS and data from a ship maneuvering simulator training center was compared in (Aarsæther and Moan, 2007) where the data available from AIS was found to be adequate for geometric analysis if a predefined plan of passage was superimposed. The accuracy of data in a real-time simulator with rudder angles and engine settings have no parallel in AIS data sets, but (Aarsæther and Moan, 2007) found that there is a geometric signature for the most common course changing maneuver, which can be derived from AIS data. AIS could be an important tool in a general case if it was possible to begin from a collection of position reports and arrive at a description of the traffic which contained both statistics for the traffic, but also a estimate for a passage plan based on a set of basic maneuvers.

The prediction in a computer simulation is based on the level of knowledge which is embedded in the models which pose a problem for simulation analysis of collision and grounding since accidents are increasingly attributed to the human element. The human element is notoriously difficult to model both for predictive and retrospective analysis, this can be addressed in simulation studies with a proper simulator facility with experienced human operators. Human-in-the-loop maneuvering simulations are an invaluable tool for training and risk analysis when the resources required are available, but there should be a reasonable alternative for the scenarios where these resources are absent. Monte-Carlo style simulations where selections of configurations and parameters are evaluated in order to provide approximate results has proven itself useful in the engineering disciplines including risk analysis. The maximum time compression determines the feasible number of variations possible to evaluate given constraints in time and computational resources, fast-time parameter and configuration studies have also been used for analysis of ship maneuvering. Large time-compression is achieved by fast-time maneuvering simulators by eliminating the human operator in the loop and representing navigation and maneuvering by software. The substitution of software in place of the human element is problematic since most accidents have a human contribution. The tendency in fast-time simulators has then been the removal or substitution of the element most prone to errors instead of constructing an appropriate model structure which can reproduce some of the behavior of the human element. It is therefore important to establish a model which present what is accounted for in the model, and how this relates to research in human factors.

A model of ship maneuvering can be constructed by separate subsystems such as the operator, automation system, the dynamic characteristic of the vessel and the environment. A proposed structure and the relationship between the components in the process is seen in Figure 1.3.1 based on the “contextual control” model of (Hollnagel, 1998) which presents a “supervisory control” model where the human operator oversees and intervenes if necessary in an automatic control system. A full working model similar to Figure 1.3.1 should be modeled in order to use simulation as a predictive risk analysis tool for ship maneuvering. Models for all the components but the human are available from hydrodynamics and automatic control where models suitable for time-domain has been developed for machinery systems, realization of environmental conditions and the dynamics of marine crafts. The before-mentioned areas has received the focus when time-domain models have been developed while human element has experienced a substitution with automatic control algorithms which represent an different system component.

Time-domain simulations of ship maneuvering have previously been applied to both retrospective and predictive analysis (Amdahl, 1980; Heldor, 1980) (Hutchison et al., 2003; Gray and E.Reynolds, 2001). Where great efforts has been made to represent the mechanics of the system, while the human operator is represented by automatic control or removed and represented as a blind-navigation model. Simulations of ship dynamic has been explored in several settings as the foundation of decision support systems, used in

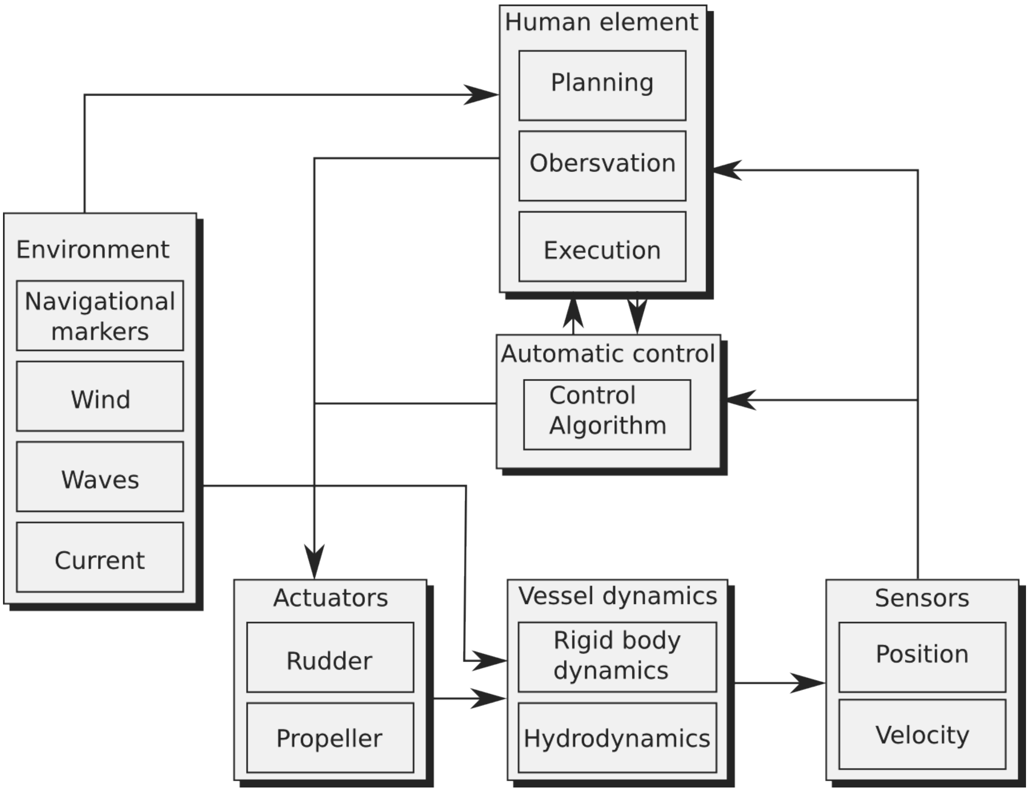


Figure 1.3.1: System description of ship maneuvering with navigation as a part of the human element. The human element appears in a supervisory role together with an automation system. This configuration of human element and control system named "contextual control" which captures the departure from manual operation and the increasing reliance on automation.

simulation studies (Inoue and Kawase, 2007) and their results applied to augmented reality displays (Porathe, 2004).

1.4 Preliminaries

Ship handling simulation has been recommended as an integral part of the design of new harbors and channels and summarized into the handbook (National Research Council - USA, 1992), where simulations have been used with human in the loop to evaluate the soundness of proposed designs. Simulations has also been used during accident analysis (Heldor, 1980; Amdahl, 1980) in order to verify testimonies and explore the immediate causes of the accident. The use of simulation in risk analysis has been limited by the availability of proper facilities for human in the loop simulations, and simulations has been used as a tool to estimate the performance of the human operator (nuclear industry). The human operator has been the limiting factor both in real-time human-in-the-loop simulations due to availability of personnel and in risk assessment in the frequency and time domain due to the problems of representing the human operator in fault tree models and fast-time simulations. This has led to the adoption of so called "blind navigation" models for simulations as applied in (Merrick et al., 2005; Merrick and van Dorp, 2006) where traffic interaction is neglected. An alternative to blind navigation is guidance and navigation algorithms from automatic control as presented by (Hutchison et al., 2003) where fast-time simulations were used in order to asses the expected number of violation of the safety zone of three proposed new bridge designs. (Hutchison et al., 2003) applied waypoint navigation in the simulations in order to control the dynamic vessels models. Use of fast-time time-domain simulations for analysis of ship traffic is a recent development and much of the focus has been on establishing dynamic models of vessels, sailing patterns and environmental effects.

The importance of the human element in maritime risk analysis has not been overlooked by risk analysts, and it has been the focus of much effort in order to include it in the analysis both as simple components in fault trees (Amrozowicz et al., 1997) and elaborate models focused on the navigational process (Fjæreide et al., 2005). The model for the human operator has received less attention in simulation studies, this might be because the use of time-domain simulation in risk analysis is a recent development and the focus has yet to shift to this area. The many types of accident which involve ships from fire, engine malfunction, structural failure, capsizing, foundering, collision and grounding. The human element is not an universal initiating event for all of these accident types, but the navigation and maneuvering process is tightly coupled with the human operator and we should expect it to be a significant component of the human element which in turn contributes to accidents. Lloyds Registry of Shipping maintain the most comprehensive database of maritime accident classified according to initiating event which includes all reported incidents which involve vessels of more than 100 registered tones[1]. Grounding and collision is a dominating accident mode which is evident in the statistics in from both Lloyds and the Norwegian Registries of Shipping (NIS and NOR) with 46% and 70% respectively (Kristiansen, 2005). (Guedes Soares and Teixeria, 2001) and (Antãno and Guedes Soares, 2008) studied the root cause of accidents involving both conventional and high-speed merchant vessels and also found that collision and grounding was responsible for a comparable number of accidents. (Guedes Soares and Teixeria, 2001) concluded from insurance statistics from the United Kingdom that 49% of accidents had an immediate cause which involved the human element and found that 80% of accidents could be attributed to human errors if design, construction and operation were included in the causality chain. The survey of high speed craft presented by (Antãno and Guedes Soares, 2008) also established the human factor as an important element in high-speed craft accidents, particularly during the operational phase.

The most severe events in ship traffic, and ultimate motivation, is collision and grounding and improvements in the methods available to predict and analyze these events is highly desirable. The illustration of the risk analysis process in Figure 1.2.3 shows quantification as an integral activity and it is the objective to develop methods to quantify the properties

[1] This includes virtually all the worlds commercial vessels, but neglects large part of the fishing fleet

of ship traffic.

Quantification of marine traffic can be achieved through direct observations which however data has been scarce and hard to obtain due to the independent nature of ship traffic. Simulations are the only alternative during the design stage and can be used with a simulation model representing the vessel as described in Figure 1.3.1, as noted above the human element plays an important role in collision and grounding and autonomous/fast-time simulation studies without an explicit treatment of the human element is a quantification with an unknown level confidence attached to the results. An explicit treatment of the human element is needed to document which effects of the human element is accounted for and how it enters the simulation. The human element has been the center of attention for risk analysis and there exits both quantitative and qualitative models of human performance but it has received little attention in simulations of ship maneuvering. Predictions are made with the purpose of communicating to others the level of "risk" which highlights the importance of transparency as it has direct influence on the confidence of third parties in the underlying model.

1.4.1 Observation

This thesis presents new methods in estimating the frequency distribution of ship traffic either by observation or by simulation. AIS is gaining momentum as an analysis tool and the system is capable of generating excessive amounts of data. The previous scarcity of data about marine traffic has been substituted by an over-abundance of data, whereas (Gluver and Olsen, 2001) installed an infrared CCTV system and (Frandsen et al., 1991) estimated the traffic density from references studies, it is now possible, with little effort, to measure the position and identity of vessels with sufficient accuracy. (Gucma and Przywarty, 2007; Gucma and Goryczko, 2007) and (Ramboll Engineering, 2006) used the system to obtain high level traffic data for use in analysis models, but did not utilize the data available form AIS to its fullest extent. This thesis has further extended the use of AIS for traffic analysis in (Aarsæther and Moan, 2008, 2009b,a) by proposing a method for automatic aggregation of AIS data into a form which greatly eases further analysis. The "simple traffic model" is presented as a by-product of this work as a the statistical summary of ship traffic is in need of a reference frame to provide the context to the statistics. The automated method for aggregation also proved capable of detecting the traffic features without any prior knowledge about existing traffic flows.

1.4.2 Ship simulation models

The frequency contribution of ship operations to risk is a broad term which need further refinement before it can be presented as a single research topic. Collision and grounding are manifestations of emergent system behavior which causes a vessel to be "at the wrong place at the wrong time". The place and time of this system state is defined in retrospect, but tools and methods which can estimate the probability of vessels present in a specific area is needed. This can be obtained from a parametric statistical model of marine traffic which is the focus of this thesis. This frequency contribution can be quantified both by observation and simulation which are interconnected by the need to model the process observed during the simulations. A traffic model which can be applied both during structuring of observations and as a framework for simulation will be presented in this thesis, together with a new method to quantify the parameters of the model from measurements. In regard to a proper risk analysis the thesis will not undertake an extensive analysis of ship traffic, but its products and procedures can support future efforts in risk analysis of ship traffic.

Simulating ship maneuvering and navigation are problems with near infinite depth, much effort has been spent on the development of dynamic models of ships, prediction of maneuvering characteristics, hull and propulsor models. The technical aspects of integration of differential equations and high-fidelity models of vessel dynamics, although required, is not the subject which determines the usefulness of maneuvering simulations as a tool for prediction. The human element, or captains mimic, is the part of the system which has the largest effect on the system behavior and which has received the least modeling attention in the time domain. Effort is required to model the complete system consisting of the environment, vessel dynamics, propulsion, control surfaces and captains mimic.

The entities which make up a maneuvering simulation can be defined as the environment, the vessel and the operator. Of these three entities the vessel and environment has received considerable attention form modelers in the form of models based on first-principles. Time-domain simulations for risk analysis is not the only application of these models and the development has been motivated by performance prediction, design and systems analysis. The hydrodynamic forces are of particular interest to maneuvering as they separate the problem from rigid body dynamics. These forces are highly non-linear with coupling effects between the motions, early attempts to model these forces were based on experimental data from elaborate experiments and full scale trials (van Berlekom and Goddard, 1972) (Norrbin, 1971). A more recent approach is to compute the coefficient based on numerical solutions of a limited set of hydrodynamic effects (Fossen, 2005, 2002). These models still rely on empirical formulations for the effects which cannot be captured by the underlying theory for the computations.

There is continuous activity in the field of dynamic vessel models (Skejic, 2008) driven by the previously mentioned motivations. Time-domain maneuvering simulations is based on these results, but the topic which separate it form performance prediction is the human operator which is in control and the result from the simulation is based on the vessel trajectory in response to the operator commands. The scope of this thesis is based on the same premises as time-domain simulations for risk analysis in general, with the models motivated by training and performance prediction with additional effort in order to model the human element. The separation of simulation and operator models is implicit in traffic simulations with "blind navigation" where the actions of the operator is accounted for in interaction situations post-facto.

Simulations of ship maneuvering has been used for several decades during design (van Berlekom and Goddard, 1972) and retrospective analysis (Amdahl, 1980) of maneuvering and navigation. The use of human-in-the-loop simulations continue to be the most reliable method as it includes the most accurate depiction of the human element possible. The development of computer hardware and software capable of simulating any reasonable dynamic system on workstation class computers has led to the application of autonomous simulations of high level ship traffic (Merrick et al., 2003) and low level maneuvering (Hutchison et al., 2003). The advances in the analysis techniques has been in the management of simulations and dynamic vessel model, while the operator present in human-in-the-loop-simulations has been replaced by automatic control algorithms. This has allowed the autonomous simulation models to increase the number of cases evaluated per time unit, at the expense of the human operator model. (Hollnagel, 1998) made a convincing argument for a schism between the use of human operator models for risk analysis and the development of models for analysis of human performance. While (Hollnagel, 1998) suggests an unified method for analysis and prediction in the frequency plane the schism still remains with regard to time domain simulations. This thesis found that the model knowledge required in order to make use of the recent advances in human factors analysis (Hollnagel, 1998) and (Hollnagel and Woods, 2005) in a simulation framework such as (Zeigler et al., 2000)was insufficient. Models based on experimental measurement such as (Hannaman and Worledge, 1988) provides a simpler model which can be used to represent the human element if the supporting systems and human elements are modeled together as a lumped system.

1.5 Objective

The objective of this thesis is to advance the estimation of the frequency component of risk quantification in ship traffic using both observations and time-domain simulations of ship traffic. Both observations and simulations are used to quantify event frequencies in maritime traffic, observations has traditionally been an cumbersome process while simulations have enjoyed the highest level of flexibility and apparent numerical precision. This thesis will develop methods for analyzing ship traffic both from observations and simulations with the intention of establishing frequency distributions of marine traffic geographic footprint and individual vessel states. Observations will be used to estimate probabilities of traffic occupying a specific area while time-domain system simulations will be used to investigate frequency estimation by simulation. There are several established models of ship dynamics in the time domain, but since there exist no comparable time-domain models for the human operator of a ship, the theory of modeling this element will be explored. This will illustrate and determine what one can expect to learn in terms of over-all system behavior from such a model, and what the model contains of knowledge. The objectives of this thesis can be grouped weather they support either quantification by observation or simulation.

Observation Observations are an important analysis method and the thesis will develop new methods to analyze ship traffic by observations and focus on developing a method which give a detailed representation of the traffic. New methods of processing collected data are needed in order to automate the collection and analysis process for large data sets which will enable a detailed analysis of a comprehensive data set.

Simulation Quantification of risk by simulation is an established analysis method, specifically the use of frequency domain models such as fault-tree models. Time-domain models are well suited for simulation since they allow for a system-of-systems approach to simulations and aggregate models can be constructed by combining models of sub systems. This thesis will use a time-domain simulation model to quantify the frequency contribution to maritime traffic risk where the representation of the human element will be integrated and receive special attention due to its prominence in accident statistics. Time-domain simulations will be used due to the availability of models and simulation technology which ease the construction of simulation models and the advantages in presentation gained from the correspondence between simulation output and observable quantities.

1.6 Scope

Risk analysis by observation and simulation is a daunting task if it were to be complete end-to-end during a thesis. Risk analysis is a broad subject and extensive effort is required to undertake the complete analysis required to model the risk of collision and grounding emerging from the operation of vessels in a particular area including both accident probability and consequences. Estimation of the probability of occurrence and the consequences of a specific scenario will usually involve different theoretical disciplines. This thesis will forgo consequence analysis and focus on estimation of probabilities by considering traffic data from a particular area selected due to a availability of data, an adequate amount of passing traffic and the presence of a harbor. This area is used in studies of observation and reused in simulation studies since the area is already established. Grounding is not studied directly since the topography of the area is not included due to time and resource constraints, neither are meteorological data. There exists data of the area, but on a form which requires further processing before it is suitable for an automated analysis. The exclusion of bottom topography and meteorological data does not preclude the analysis technique to be combined with such a data sources in the future, as they are independently recorded but any coupling to the observed ship traffic will still be present. The treatment of quantification by observation in this thesis will focus on developing models and methods for analysis of data of ship positions which are contained within closed geographic region.

Quantification by simulation will be investigated in the geographic area which was used for observation, but care must be taken to document the effects included in simulations as the effect of features missing form the simulation model will be missing from the results, in contrast to observations where any effect present will be accounted for by the observation target. The simulations will be system simulations of the ship navigation and maneuvering process in the time-domain and will reuse existing models. Standard models for ship maneuvering will be applied together with a model for the area containing current and navigational makers together with model for a navigation and maneuvering which will be developed. The model for navigation will be presented as closely coupled with a geographic area and not capable of accounting for interfering traffic. The original contribution will be on formulating a model for the combined navigation and maneuvering process which can be used in the time-domain. The resulting model will be used in a Monte-Carlo style simulation to show how the model performance in a typical quantitative analysis setting.

1.7 Thesis outline

The thesis is focused on quantification of the frequency of ship positions and is organized as an introduction, two sections witch independently treat quantification from observation and simulation and finally conclusions and recommendations for future work. Quantification by observation is presented first since quantification by simulation is dependent on the structures devised for the analysis of observed traffic data. This thesis is a summary of journal and conference papers published during research around frequency estimation for collision and grounding. The thesis is supported by the following conference and journal papers:

Background

- **"Combined Maneuvering Analysis, AIS and Full-Mission Simulation"** (Aarsæther and Moan, 2007), conference paper presented at the 7th International Navigational Symposium on Marine Navigation and Safety of Sea Transportation, Gdynia, Poland 2007

Main papers

- **"Autonomous Traffic Model for Ship Maneuvering Simulations Based on Historical Data"** (Aarsæther and Moan, 2008), conference paper presented at the 7th International Conference on Computer Applications and Information Technology in the Maritime Industries
- **"Estimating navigation patterns from AIS"** (Aarsæther and Moan, 2009b), published in the Journal of Navigation Volume 62, Issue 4
- **"Computer Vision and Ship Traffic Analysis Inferring Maneuver Patterns From the Automatic Identification System"** (Aarsæther and Moan, 2009a), conference

paper presented at the 8th International Navigational Symposium on Marine Navigation and Safety of Sea Transportation, Gdynia, Poland 2009

- **"Adding the human element to ship manoeuvring simulations"** (Aarsæther and Moan, 2010), published in the Journal of Navigation Volume 63, Issue 4

The thesis is organized into four chapters with Chapter 1 describing the background, Chapter 2 covering observations and analysis of ship traffic, Chapter 3 deals with analysis by simulation and Chapter 4 contains the summary, conclusion and future work. The papers and the chapters covers the same topics and the thesis is intended to summarize the findings of the papers and present them in a unifying context.

(Aarsæther and Moan, 2007) is a pilot study on the differences between analysis by real-time simulation and data obtained from the Automatic Identification System and should be considered as preliminary study before the main research. The development of the observation method for ship traffic presented in Chapter 2 is essentially covered by (Aarsæther and Moan, 2008, 2009b,a) which show the development of the method from concept to a established method. Chapter 3 on analysis by simulation is supported by the material presented by (Aarsæther and Moan, 2010) and partly by the considerations of simulation in (Aarsæther and Moan, 2008).

The original contribution of this thesis lies in the quantification of observed ship traffic which is the first application of computer vision in order to detect traffic features and aggregate the measurements into an analysis base suitable for generating frequency distributions of ship traffic. The majority of time was devoted to the development of this method since a foundation built on measurements was considered important for any work to have practical value. Quantitative simulation studies have previously been applied, but have focused on the technical system on the ship. This thesis will also consider models of the human element and if existing models can be integrated in time-domain maneuvering simulations.

Chapter 2

Analysis of ship traffic

Several approaches have been developed in order to quantify the frequency of ship traffic properties, either to estimate traffic density as analysis input or as a complete model to measure risk. The approaches vary from direct measurement of ship traffic, analysis by simulation and statistical models. The basic premise being that knowledge of the navigation patterns in an area is required together with a statistical description of the traffic in order to make predictions about risk levels.

Marine traffic patterns are in the general case undefined and show little resemblance to the well regulated road or air traffic. Externally imposed travel restrictions are limited to IMO mandatory traffic-separation schemes and local markers signaling danger and forbidden areas. The traffic passing through an area is therefore, in all but the simplest cases, not likely to follow a predefined pattern which can be extracted form nautical charts[1], but develop a pattern on its own from physical limitations and operational habits. While the traffic patterns can be reasonably estimated form expert opinion the statistical description of the traffic must be derived from measurements, were variables of interest include the inter arrival time (traffic density), the speed and the cross-track spread (traffic width and placement). Observation of real world ship traffic is required before statistics can be established, but the choice of statistical variables also imply an underlying model of the traffic. The distribution of the course angle, the speed, or the spread from an imagined center line does imply a traffic model where the statistical properties are sufficient to define the traffic shape and behavior.

[1]There exist traffic restrictions, but based on size and draught. Even the IMO traffic separation schemes cannot be studied without considering interfering traffic (such as channel ferries crossing the Dover traffic separation scheme). There is no equivalent in vigilance and authority to the aviation infrastructure air traffic control.

2.1 A model for traffic-patterns

A model for a traffic pattern which is more descriptive than a simple averaging of variables across a geographic domain will contain a basic set of maneuvers as building blocks used to construct the emergent shape of the traffic. The simplest maneuver possible is to maintain a steady course which is the foundation for the implied model behind a statistical description of traffic with regard to a imagined center line. A straight course traffic model will in the general scenario fail to capture the traffic patterns as positions will fail to conform to the model. An extension of this simplistic model with course changes is the simplest traffic model which one can expect to capture the features of traffic patters of ship maneuvering. Such a simple model of a singe traffic pattern with the parameters needed to define it is seen in Figure 2.1.1 where a simple example with three legs with constant course is shown interconnected with tangential circles. The figure shows the geometric shape of the traffic pattern, but density is an additional variable which is defined by the time between consecutive arrivals of vessels. As seen in the figure all the pattern sections are associated with a speed and the straight sections are defined by the desired heading. The circle sections represent regions where the traffic changes direction. Course changes are determined by the curvature, κ, of a circle placed tangential to the adjacent sections. This underlying model for a singe traffic pattern is inspired by the procedure for passage planning reported by (Lützhöft and Nyce, 2006) and as an artifact of planning can be seen in the passage plan representation shown in (Amdahl, 1980) and (Laforce and Vantorre, 1996). An underlying simplification of this simple traffic model is that it does not account for interaction with other vessels, which can be further exploited to represent the traffic in a selected area by superposition of mutually independent traffic patterns. This assumption introduces a limitation which must be considering when interpreting any results derived from the model.

A statistical representation of the parameters in this model must be populated by measurements which provides a quantification of the speed and spread of the traffic. Quantification of the parameters should be possible if the model is to be of any practical use. The quality of parameter quantification is dependent on the technique used to collect and refine the data. Individual traffic patterns can be collected based on prior information that provide a set of rules to identify data belonging to the pattern (Aarsæther and Moan, 2007).

2.2 Measurement of ship traffic

Measurement, or observation, of ship traffic is required in order to quantify the statistics to complete the model from the previous section. Quantitative measurement of ship dynamic response and performance has been an integral part of sea-trials and design verification. The effort by the IMO to improve the maneuvering performance by standard requirements led to the installation of position reference systems of adequate accuracy during sea-trials making performance data available as in the case of the Esso Osaka and Esso Bernica.

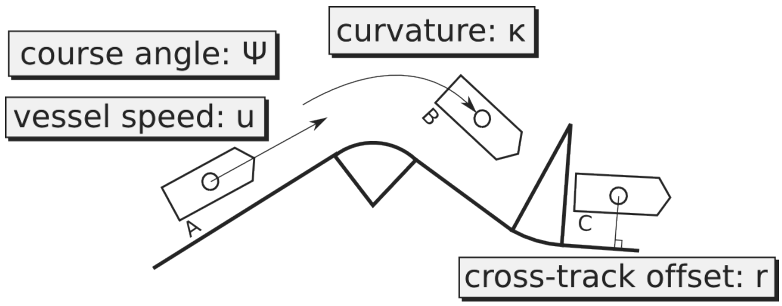
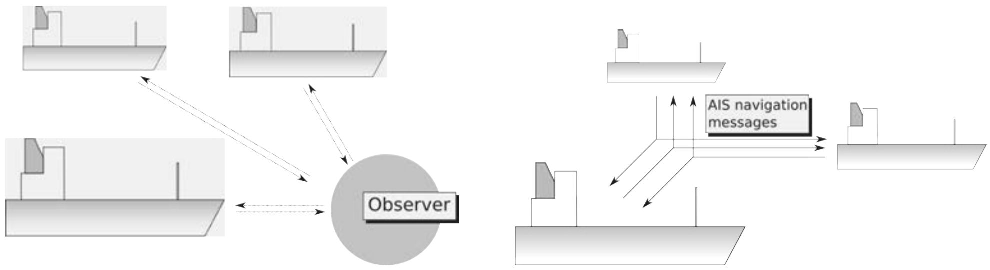


Figure 2.1.1: The simple model for a single traffic-pattern with straight sections interconnected by circular turn sections shown in bold. The statistical variables are shown on the vessel imprints along the traffic-pattern.

GPS introduced a standardized measurement source for the ship position, and has become an integral part of the on-board navigational equipment. The deployment of positioning systems on ship has been focused on determining the ships position for use in navigation with the possibility to record the data for later use. The availability of high accuracy GPS implementations has brought increased accuracy to the measurement of ship traffic, but GPS in isolation has had little impact on the quantification of traffic as the measurements are isolated to a single ship. The autonomous nature of ships implies that a large effort to collect data recording devices would have been required in order to rely solely on the GPS reference system to produce a coherent data of regional ship traffic. There are two distinct system architectures for observation of ship traffic, centralized observation (remote sensing) and distributed collection of local measurements. This distinction is seen in Figure 2.2.1 where distributed collection is represented by AIS. AIS has the potential to solve the problem of collecting position logs from different vessels but will degrade the accuracy of the GPS measurements due to the limited payload in a singe AIS message. Another distinction between these two collection regimes lines in the effort required to accommodate the observer. A centralized observation relies on querying every ship for its position whereas the distributed approach accommodates the observer by listening to the ongoing exchange of messages.

2.2.1 Purpose built systems

The alternative to a systematic collection of GPS position logs has been to construct shore-based measurement systems to remotely determine and track the position of vessels. Such systems have been constructed using infra-red closed circuit TV (CCTV) (Gluver and Olsen, 2001), radar (Pedersen, 2002; Yao et al., 2010) and laser range finding (Zalewski and Montewka, 2007; Gucma and Montewka, 2005). Purpose built monitoring systems were long the only reasonable alternative for shore-based traffic measurement. The additional hardware required for these systems require investment in equipment and time. The accuracy of purpose built systems can be as good as the hardware allows, with laser based range-finding the most accurate but the drawback are the required investment, the



(a) Basic architecture of remote monitoring of ship traffic by a centralized observer. The quality of the measurement data depends on the observer and the technical abilities of the system obtain accurate measurements at a distance.

(b) Autonomous exchange of AIS transmissions between vessels, there is no significant difference between an observer and a vessel which is observed.

Figure 2.2.1: The different architectures between central observation of ship traffic and distributed measurements broadcasted over AIS

temporary nature of the installation, the sensitivity to prevailing weather conditions but more importantly the centralized nature of the systems.

The underlying architecture of purpose built systems are that of a centralized observer as seen in Figure 2.2.1a. The observer must classify the objects in the area, observe the state (position) of objects and record them. This system architecture place several functions at the observer in addition to the pure record keeping function. This system architecture has an impact on both the quality and quantity of measurements available form these systems. The infrared CCTV is limited by the resolution of the CCTV signal which has implications for the resolution of the position estimate. Observations form laser range finding will give high-fidelity measurements of speed and position, but is limited by visual conditions and the number of objects required to be observed simultaneously. Radar is the most robust of these techniques as it allows observation of all the objects in range but is also the most expensive. The accuracy of radar is highly dependent on the type of radar in use and the range to the object of interest and a direct recording of the radar output is a technical challenge, and also subject to stringent access controls (Yao et al., 2010). All the systems described previously are based on direct observations and can have issues with coverage due to the local topography.

2.2.2 The automatic identification system

The automatic identification system (AIS) for ships was introduced to augment radar observations with broadcasted vessel positions unaffected by local radar shadows. Radar was long the primary information source of the position of other vessels, while electronic and celestial navigation provided the global position of the local ship. The quality of the local position service was greatly increased with the introduction of GPS while the quality of position information of other vessels continued to be determined by the capabilities of the radar equipment. AIS for ships was introduced by IMO through the SOLAS convention to augment ship borne radar for navigation and to boost the capabilities of land based vessel traffic services. The motivation of the system was the availability of precise satellite navigation system (NavStar GPS, Glonass and the future Galileo system) on each vessel, which with the correct infrastructure in place can be used to improve the precision of other vessels knowledge of the local vessel position. The system is based around shipborne radio transponders and land-based base stations communicating over two reserved channels in the VHF frequency band. The SOLAS convention was amended to require all ships above 500 gross-tones in domestic traffic and 300 tones in international traffic to carry AIS transponders. The transmissions are self organizing and the transponders does not need a central system to organize transmission times or re-transmit received data to other vessels. AIS achieves autonomous operation by a time-division-multiplexing algorithm, the ITU defined standard for AIS provides 4500 time slots pr minute while the time division multiplexing algorithm gives the system the capability to degrade gracefully by giving priority to transponders in the proximity. The data transmitted by an AIS transponder is separated into three classes depending on the dynamic nature of the message contents

Static data Data which are presumed constant during the vessels lifetime: The unique MMSI number, call-sign, vessel type, vessel length & beam and location of the satellite positioning antennae

Voyage static data Data which are presumed to be constant during a voyage: Type of cargo, destination, estimated time of arrival and vessel draught

Dynamic data Data which change based on the state of the vessel: Navigation status, position, speed over ground, course over ground, true heading and rate-of-turn.

The transmission rate for the static and voyage related data are once every 6 minutes, or when polled for the information. The dynamic data is transmitted on varying rates depending on the navigational status of the vessel. The full list of sample rates for the dynamic data is seen in Table 2.1 where sample rates ranges from 3 minutes to 2 seconds. For ships at moderate speeds there are position updates every 12 seconds during course keeping and every 4 seconds while changing direction. The sample rate increases with increasing speed and it should be apparent that accumulation of dynamic data from AIS will result in a extensive data set of ship movements.

2.3 Data collection, processing and reconstruction

Distributed data collection over AIS is preferable to centralized collection with purpose built systems. Due to its ease of use and coverage AIS provides a flexible and comprehensive method of collecting the traffic data needed to populate the statistical properties of the traffic model. AIS combines position,orientation and speed reports of reasonable accuracy, unique identifiers for each vessel with easy availability. AIS broadcasts are not

Table 2.1: Transmission rates for dynamic AIS data, including ship speed, course and position

Navigational status	**Transmission rate**
Ship at anchor	3 minutes
Ship at 0-14 knots	12 seconds
Ship at 0-14 knots and changing course	4 seconds
Ship at 14-23 knots	6 seconds
Ship at 14-23 knots and changing course	2 seconds
Ship at more than 23 knots	3 seconds
Ship at more than 23 knots and changing course	2 seconds

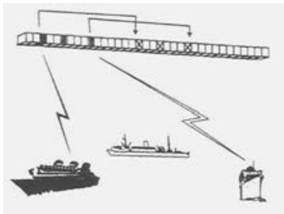


Figure 2.2.2: Transmission slots and transmissions of AIS data using a time-division multiplexing algorithm. Each transponder independently determines a suitable transmission slot by inspecting the timing of received messages. Figure reprinted from (International Maritime Organization, 2001)

subject to legal limitations and are broadcasted unencrypted, this allows any properly constructed receiver or transponder to collect AIS messages from vessels in VHF range. The infrastructure is in place for normal operation since AIS is mandated and the use of AIS for traffic analysis can be assisted by the government bodies responsible for a country's AIS installations. The Norwegian Coastal Administration was helpful in providing the AIS data where a subset was used in (Aarsæther and Moan, 2007, 2009b, 2008, 2009a), but a single AIS receiver should be sufficient to make observations in the area presented.

Data form AIS is captured as discrete messages on two VHF channels. The protocol is lightweight and the message contents is the only way to identify the sender and time of transmission. The AIS message that contains dynamic vessel data is designed to be self-contained and does not require knowledge of previous messages. This implies that there is no data-stream which one is accustomed to from measurement devices, the individual dynamic data messages must be collected into groups to represent a coherent analysis base. The reconstruction of the time series should be based on the time-stamp (time of transmission) and the unique MMSI number contained in each dynamic message. This makes the collection of position reports into groups based on MMSI number and arranging them by time straightforward.

(Aarsæther and Moan, 2007) built an SQL database of position reports indexed by MMSI number and time-stamp which could be queried at a later time limited by an arbitrary

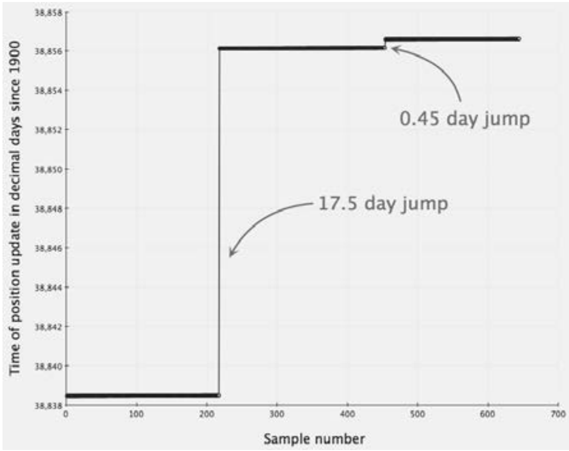


Figure 2.3.1: Discontinuities in the time-stamp of AIS position reports belonging to a single MMSI aggregated time-series

geographic region and provided a time ordered stream of position reports from a single MMSI number. The stream of position reports might contain time-series of multiple voyages at different times since the data is aggregated based on MMSI number and an example of this is seen in Figure 2.3.1 where the time-stamps from a single MMSI number data stream is shown. These time-stamp discontinuities are a result of a vessel leaving and reentering an area, and the “contiguous” sections of time-stamps represent single voyages which can be separated from the data stream based on the time-stamp differential.

A single MMSI aggregation may also contain a data stream of a vessel which enter the area and proceeds to a harbor. These data streams can be refined into single voyages by considering not only the continuity of the time-stamp but also the magnitude of the vessels speed over ground since a stationary vessel should not be included in the statistical base of traffic patterns and neither should the continuous stream of position reports with stops at a harbor give rise to a single traffic pattern, but to two patterns entering and leaving the harbor. A single voyage can be separated from such a stream if the speed of the vessel drops below a defined threshold. The combination of these procedure results in a set of time-series of dynamic AIS data which each represent a single voyage which can be used to build a statistical description of the traffic patterns.

2.4 Single voyages to aggregated traffic patterns

While the accuracy and sample rate of data collected from AIS is of sufficient fidelity for analysis, data from a small selection of voyages will not reveal the predominant traffic patterns in an area and will not provide a dataset of sufficient size to derive adequate statistics. A large number of data series must be collected during a long interval which is trivial with AIS as long as the data is stored for later use. The challenge when working with AIS to analyze traffic is not to acquire the data, but analyze it efficiently in order to take advantage of the large number of observations. AIS is a continuously observing system and will during a three month period with a small number of passages (10 pr day) generate in the order of 1000 position series. Manual processing of data-sets of this magnitude quickly become infeasible, especially considering 10 passages pr day represents a very modest density. An automatic method for aggregating individual time-series into groups of similar voyages is an prerequisite in order to fully exploit the AIS data. A method of converting individual dynamic AIS messages to data streams from individual vessels was presented in the previous section, but only represents a transformation from disjoint observations into a base for analysis.

Since the simple traffic model is an idealized geometric structure the analysis of vessel traffic must begin with an separation of the geometric traffic patterns present and associating the vessel tracks with the different groups. Aggregating time-series from AIS based on the path taken through an area is essentially a problem of pattern recognition. If the task was to be completed manually the decisions about which time-series formed a group of similar traffic would be based on a subjective measure of similarity where the operator would assess the geometric properties of two specimens and classifying them based on the question “are they similar?”. Automatic comparison of the similarity of objects has long been studied in computer vision in order to have a computer algorithm separate the contents of an image, determine the features of the objects present and to decide if the same object is present in several images. The results produced by these algorithms can be seen in satellite image mapping programs where they are used to stitch together overlapping aerial photos. The body of knowledge represented by the developed algorithms for image processing is a valuable resource which can be applied to other problems, if the problem lends itself to an image representation where a bitmap image is composed of one or more matrices of color intensities.

Before one can start to analyze the data streams one must decide what to analyze, in this case the obvious answer is to analyze each individual data stream based on the time-series of the position which leaves a trace through the area. Transfer of a time-series of position data into an image representation can be achieved by discrertizising the area (matrix formulation) and counting the number of position reports in each discrete region (color value). This transfer of remotely sensed data into a known representation achieves additional benefits since the camera position and exposure/capture conditions for the image is controlled by the application. This simplifies further analysis as the problems of different exposure, lens distortion and camera orientation can safely assumed to be absent.

The first attempt at aggregating vessel tracks by image processing from (Aarsæther and Moan, 2008) was based on comparing exaggerated, a reduction in resolution, track-lines in place showed promising results. The direct comparison procedure is illustrated in Figure 2.4.1 where both the original and exaggerated representations and the difference between them are shown. The figure shows that a successful match of two vessel tracks can be expected if the track placed the vessels at similar positions along the track, however the comparison will fail if the tracks are on opposite extremes of an imagined mean track-line. This effect can be suppressed by extending the exaggeration of the track, but this will influence the methods ability to distinguish between different paths. Introduction of an optimization of the attainable similarity between tracks during a translation on a planar surface (Aarsæther and Moan, 2009a,b) is a superior alternative to lowering the resolution. The process of aggregating the vessel tracks into groups of similar shape is dependent on two main components:

1. A computation of a number to indicate the degree of similarity between two image representations of the time-series.
2. An optimization algorithm to derive the maximum attainable similarity between two images.

Comparison of two images in matrix representation is in the basic case to subtract the pixel values of one image from the other. This naive method will only detect a similarity between images which are very similar. One of the images can be translated in both directions by u and v pixels in order to account for a translation of the original image. The computation of a scalar degree of overlap between two such image matrices is seen in Equation 2.4.1 which shows a numerical measure of similarity between tow images under a translation (u, v) where the result is normalized by the total number of pixels in the original image. The equation can also act as the objective function of an optimization problem where $Similarity(u, v)$ is minimized by optimization of the (u, v) translation.

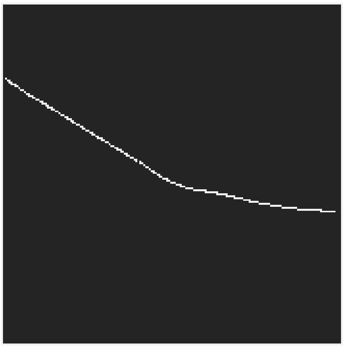
$$Similarity(u,v) = \frac{\sum_{x=1}^{N}\sum_{y=1}^{M} I(x,y) - J(x-u, j-v)}{\sum_{x=1}^{N}\sum_{y=1}^{M} I(x,y)} \tag{2.4.1}$$

The measure of similarity is a non-linear two dimensional function in u, v space with the possibility of several maxima. The function for image representation will have a pronounced peaked surface with a high maxima. Two dissimilar images will naturally produce a lower maxima but the function will also produce a surface without a clearly defined peak feature. Numerical optimization methods are well suited to find the maximum similarity between images in the u, v space.

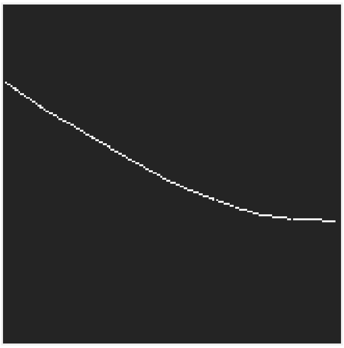
The optimization method can be used iteratively on the available time series by starting with a single-time series as a representation for a group. The group will then be constructed by aggregation of each new time-series to update the group representation by averaging the data from the group members and will continue adding both new time-series and merging groups until further iterations produce no new aggregations. This approach provides an automatic grouping of single vessels tracks based on the geometric shape of the tracks.

2.5 Traffic pattern analysis

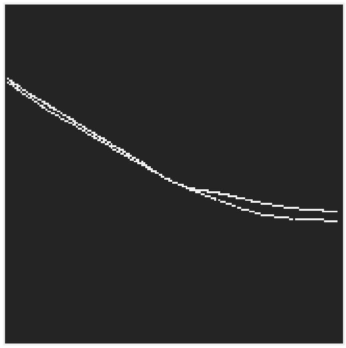
The results of the image registration aggregation in the previous section is seen in Figure 2.5.1 which shows a the separation of traffic into distinct groups. The AIS data of the



(a) Original vessel track (a) image representation



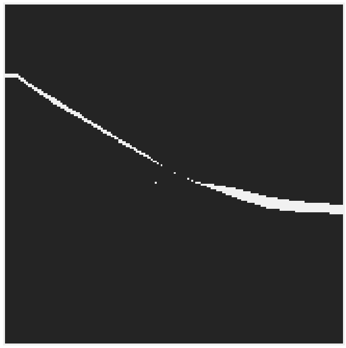
(b) Original vessel track (b) image representation



(c) Direct comparison of vessel tracks (a) and (b) with no overlap detectable

(d) Exaggerated vessel track (a)

(e) Exaggerated vessel track (b)



(f) Direct comparison of exaggerated vessel tracks (a) and (b) showing overlap

Figure 2.4.1: Comparison of vessel tracks by comparison by superposition of original and exaggerated vessel tracks

vessel tracks can now be used to derive the statistics of the simple traffic model which can be used as a starting point for analysis. While other works which employ AIS focus on high-level statistics (Ramboll Engineering, 2006), this separation of traffic allows the traffic to be analyzed conditioned on the preferred path. This structure also supports the view of collision risk as presented in Figure 1.2.4 and in (Pedersen, 2010) since the estimation of the probability of the vessel placement is straightforward from the format of the processed data. There are no fixed measurement locations as with laser measurements since the AIS data from vessel tracks are of an homogeneous nature both in speed and in sample rate. A conversion to a more orderly format is required if measurements are to be related to geographic locations along the groups track which is also necessary to support the construction of the constant and course changing sections of the simple traffic model. A geometric relationship between the AIS variables, and a computed curvature, was constructed in (Aarsæther and Moan, 2009b, 2008) by adopting a discretizised model of the traffic group geometry and relating the individual observations to discrete group points as seen in Figure 2.5.2b. The group geometry can then be separated into the elements of the simple traffic model by considering the curvature variables at each discrete group point. This process is seen in Figure 2.5.2 where one of the groups of Figure 2.5.1 is discretizised and converted to a simple traffic model description. The statistical description of the simple traffic model is a byproduct of the construction process and provides the answers to the probability distributions of course, spread and speed required to quantify the frequency component of the risk associated with the current traffic.

A description of the plan behind the maneuver pattern is a requirement in order to understand not only the sequence of maneuvers but also by which rules the vessels are piloted through the area. These rules does not only help to understand the traffic, but is also required for detailed analysis by traffic reproduction with simulations. The reduction into the simple traffic model allows re-processing of the data with the traffic model as a reference which can determine a plausible proposal for a navigational plan that satisfies the simple traffic model. The relationship between a navigational plan and the environment described in (Lützhöft and Nyce, 2006) where navigational markers used during the transition between constant course sections are the primary reference to the environment. The connection between the transitions in the traffic model and the surrounding environment must be established before the data of the model can be used as a starting point for traffic simulations. The navigational markers in the environment is a general term with every visual object belonging to the set, but the purpose built navigational markers acts as a minimal set for this term. Man-made navigational markers are publicly maintained installations and the Norwegian Coastal Administrations maintains an open-access machine readable databases of the installation in Norwegian waters which covers the geographic region used in (Aarsæther and Moan, 2008, 2009b). This database can be used together with the simple traffic model to construct a relationship between the traffic and the area as represented by the markers. The placement of the vessel in relation to the environment determines the time of transition between a set of planned maneuvers. The position of the vessel is determined by identifying and observing the bearing and distance to markers while rules of thumb suggests favorable markers for specific transitions. An analysis of

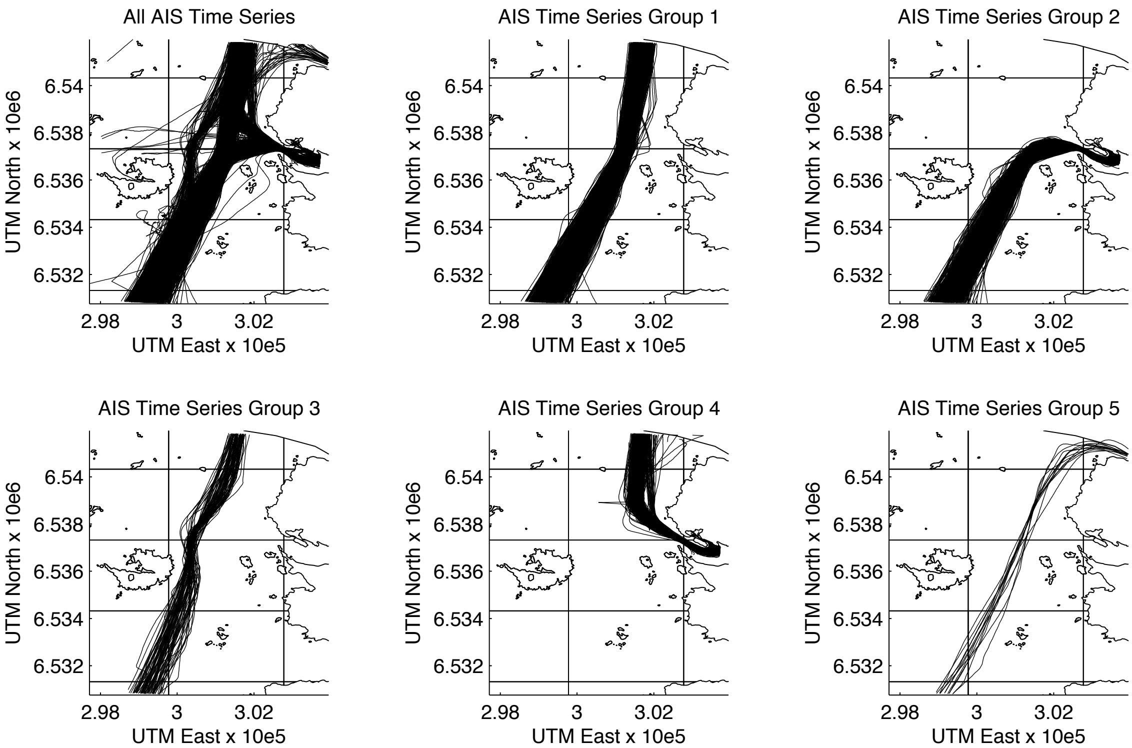
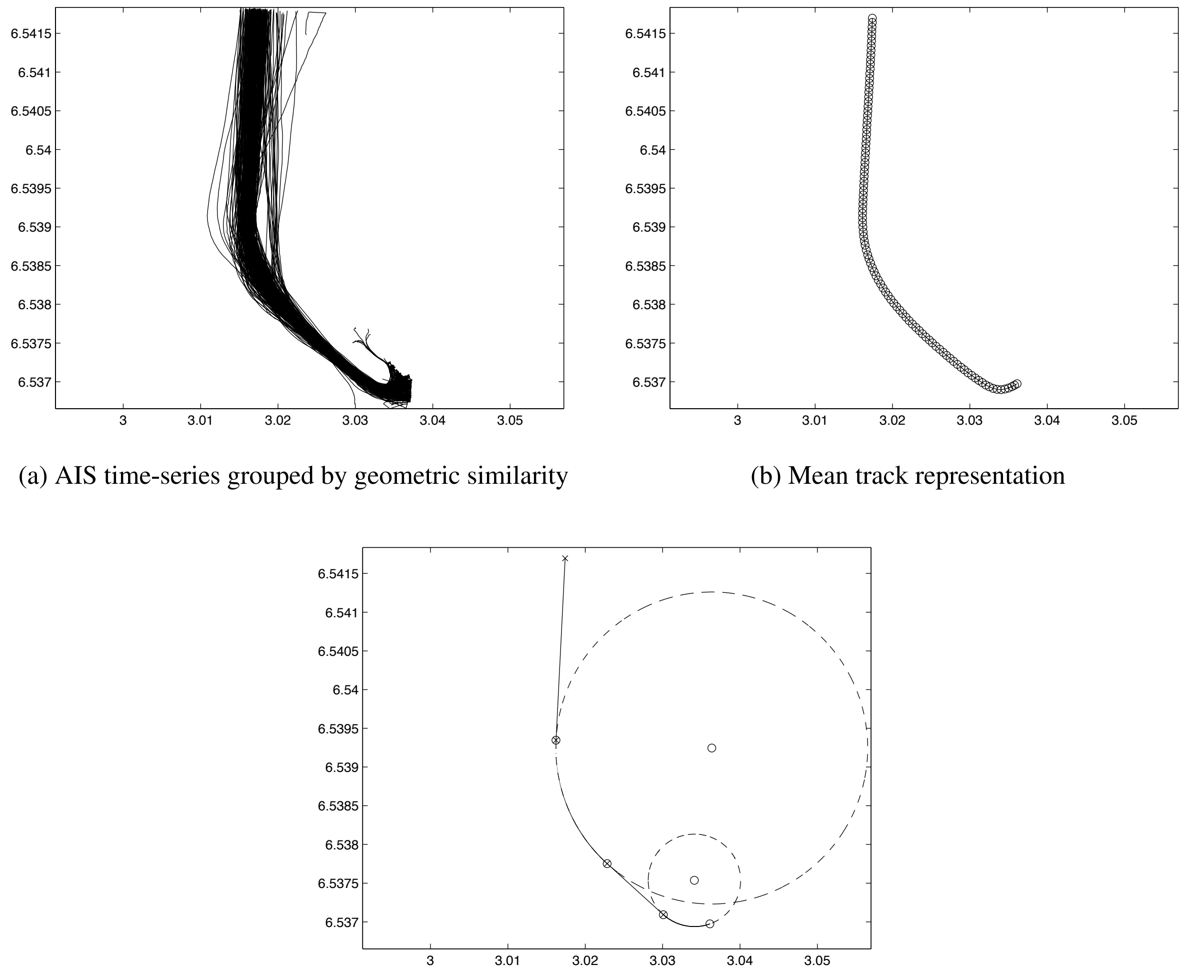


Figure 2.5.1: Results of application of image correlation based aggregation of AIS time-series. The procedure produces sets of traffic following similar paths and reveal a traffic pattern which is hard to discern in the original AIS data



(a) AIS time-series grouped by geometric similarity

(b) Mean track representation

(c) Idealized track description

Figure 2.5.2: Representation of a directional traffic pattern as a set of time-series, a mean track and as an idealized traffic model.

the relationship between maneuver transitions and markers in an area requires the bearing and distance of navigational markers at the individual voyages transitions. This carries with it the implicit assumption that the individual vessel tracks follow the pattern established by the simple traffic model and that the criterion for identifying the navigational markers in use captures the actual behavior. The results of this process can be seen in (Aarsæther and Moan, 2009b,a) and completes the process of converting observations of marine traffic to a statistical description which can be used as input to both risk analysis and further simulation studies.

Chapter 3

Simulation of ship maneuvering

The previous chapter presented a technique for observation and analysis of ship traffic based on AIS. Observations will always remain the most reliable quantification of frequency were the current situation is of primary concern. Reliance on observation is insufficient if the scope is extended from the current situation to abnormal situations not present in the data set or during a design stage. Exploration of accident scenarios and new installations are not suitable for historic traffic data where the vessels follow the same traffic pattern and one has turned to simulations for exploration.

Quantification of the probability of succeeding, or failing, during the steps needed in order to avoid collision and grounding have been studied in (Amrozowicz et al., 1997; Chen and Moan, 2004; Kaneko, 2002; Fjæreide et al., 2005), but these studies lack the dynamic behavior of vessels needed to produce a synthetic marine traffic. There have been few simulation studies of ship maneuvering where the traffic and behavior of the ship has been the objective instead of determining and illustrating dynamic models. (Hutchison et al., 2003) used a systematic set of both autonomous fast-time and human in the loop real time simulations to predict the placements of ships in relation to three new proposed bridge designs. (Goerlandt and Kujala, 2010) recently presented a study of traffic in the Gulf of Finland where simulations were used to recreate current traffic conditions. Quantification of frequency distributions with simulations benefit from large number of data points and fast-time simulators are an attractive option in order to reduce the resources required, and the barrier of entry, for simulation studies. The necessary of removing the human operator form the loop in fast-time simulators has left the responsibility of representing the human operator to automatic control.

While automatic control is increasingly popular and capable during cruising and in dynamic positioning applications, the context where the navigation and maneuvering processes takes place require an entity which is capable of making use of different informations sources of varying types and adaptation to a changing environment. Autopilots are at a disadvantage from human operators since the waterways are instrumented and regulated with a human operator in mind. The present function of autopilots are for simpler maneuvering tasks and are not built to be aware of other vessels and does not include the knowledge of local conditions acquired during the pilot certification process. Autopilots perform only the simplest maneuvers in confined waters such as course and station keeping, while the officers on watch supervise, decide and perform the actions required for safe transition in confined and congested waters. The successful completion of a ships journey involves several stages which includes voyage planning, execution and observation. The substitution of automatic control for the human element effectively neglects its role, the representation, or removal, of the human element should be explicitly treated in order to emphasize what is included or neglected in the simulation model. Models for analysis and prediction of human performance are plentiful, ranging from early functional methods designed in order to accommodate the needs of fault tree analysis to detailed models of human cognition used to study man-machine interaction.

3.1 Models of the human element

No system is built by itself and only the most basic engineering system is fully autonomous. The most common configuration of transport or vehicle systems involve a human element either assisted by automation and powered actuators or in a supervisory role. As the reliability of engineering systems, be them mechanical or electrical, has increased, it has become obvious that the human element present in system design and operation has emerged as the dominant source of errors in the system. To account for the human element as a component which influence the reliability of the system it became necessary to include the human element in predictive reliability analysis. The need to include the human element in reliability analysis was prompted by engineers and the first attempts to answer the question of "human reliability" where heavily influenced by system reliability analysis. The methods emerged in direct response to a engineering need and are by (Hollnagel, 1998) classified as "First generation human reliability analysis methods" due to their lack of an explicit model for human performance. Later efforts to develop human reliability analysis methods has been influenced by retrospective analysis and the need to provide a model for human performance that can be used for analysis of causal chains involving a human operator. Human reliability analysis can be defined as a process to minimize the risk associated with the system by optimizing the conditions of the human operator. The process can be conceptually divided into the following three stages.

1. Identification of human operator actions and the failure modes
2. Quantification of the associated failure probabilities
3. Reduction of the error probability if the combination of consequence and frequency is unacceptable

Human operator actions should be identified as a part of the formal safety analysis of the system. The crucial analysis element is the quantification of the associated human performance as it has direct implications on the overall system analysis and the effort expended in order to minimize the frequency of errors.

Methods for predictive quantitative assessment and analysis of human reliability was developed as a necessity rather than through theoretical deliberations. This resulted in an initial set of methods which was created to directly address the problem of including the human element in PSA. As identified by (Hollnagel, 1998), all techniques to analyze human reliability must include the following components

Model A conceptual model with the components identified to be necessary for human performance

Method A clear and structured mechanism of how to apply the analysis technique

Taxonomy Definition of the terms applied in the technique and the underlying meaning of the terms

The need for a model of the human operator which provides more detail for retrospective analysis led to the development of several sets of model-method-taxonomy systems. The level of detail in the model, method and taxonomy triplet varies with the method, but can be said to be more consistent in later methods as opposed to the early methods developed to include HRA in PSA. The model of the human element as a information processing mechanism can be seen as a further development of Rasmussens skill-rule-knowledge framework.

The need to include the human element in formal safety analysis has had a profound influence on the practical applicability and theoretical foundation of the "First generation" of human reliability analysis methods. The first generation methods all share the feature that they provide a probability of failure, the performance of the human operator is reduced to a number that indicate the probability of success/failure.

3.1.1 Quantification of human error probabilities

The central part of the human reliability assessment is the quantification of error probabilities. The results of this activity determine the focus of actions in the subsequent stage to increase the system reliability. The definition of a human error probability (HEP) is defined in Equation 3.1.1 where a prototypical error probability can be calculated if it was possible to observe both all the possibilities of a particular error and the actual number of errors.

$$HEP = \frac{Number\, of\, errors}{Number\, of\; opportunities\, to\, commit\, errors} \tag{3.1.1}$$

This observation poses a problem for all cases except laboratory exercises (or training simulators), and specifically for where the system under analysis is hypothetical or at the design stage. This simple definition of a human error probability might give the impression that the notion of human error is a clear cut case of simply observing a clearly defined process. (Hollnagel and Woods, 2005) and (Hollnagel, 1998) describes an increasing trend in the attribution of root causes to the human element and notes that the search for a human in the causality chain will succeed since no system is designed, constructed or operated without human involvement. The "Number of opportunities to commit errors" is therefore not a constant, but rather dependent on the observer. Simplified methods which rely on other sources of information have been developed to address this and range in complexity and model fidelity.

The stimulus-response model The simples method to model the human operator is based on the notion of the human operator as a simple stimulus-response mechanism where a signal prompts the human operator to complete a task and the operator completes the task either with success or failure as the outcome. The formulation assumes that there is a prototypical success probability of human actions independent of operator and external factors.

This assumption will obviously fail to capture a variety of operational situations where operators will have a varying level of training and skill set, together with organizational and ergonomic factors which will influence the level of performance. The stimulus response model can be extended to include the effect of external factors such as physical work environment, time of day, the level of training by the inclusion of performance shaping factors (PSF). The probability of human error is then calculated as shown in Equation 3.1.2 where P_{he} is the resulting probability of human error, HEP is the prototypical human error probability, PSF_i is the ith PSF and W_i is the weighting associated with this PSF.

$$P_{he} = HEP \cdot \Sigma_{i=1}^{n} PSF_i \cdot W_i \tag{3.1.2}$$

An illustration of this model formulation is seen in Figure 3.1.1 where the view of the human element of a processor which respond to a "call to action" is evident. A number of methods to estimate the probability of failure/success associated with human actions has been developed, but most of them share the same basic methodology, an estimation of a resulting success probability from the combination of a core prototypical error probability with a set of PSFs. The quantification of the error probabilities differs between proposed methods, but range from databases (THERP method from (Swain and Guttmann, 1983)), estimation of probabilities from at least two known success probabilities (SLIM method from (Embrey et al., 1984)) and pure expert judgment (HEART method from (Williams, 1985)).

Information processing model The simple stimulus-response methods include an implicit model of the operator which contain no internal structure. These models are unsuitable in retrospective analysis of accidents as they provide an insufficient internal structure to relate to possible root causes. More elaborate models for the human operator that included an internal structure were developed to address these shortcomings. From retrospective analysis the models inherited the focus on the mental and cognitive capabilities

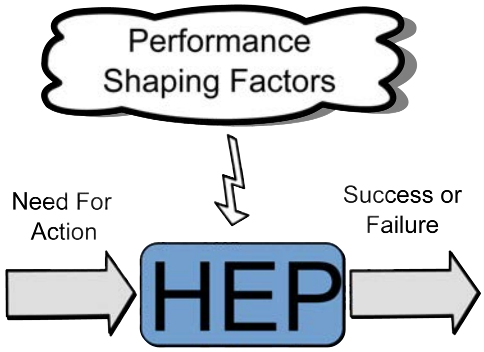


Figure 3.1.1: Human error probability as an intrinsic property of the operator. The performance shaping factors influence an already known idealized success ratio.

of the operator as identified as major contributors to accidents. A model of the human operator where information in a sequential manner is acquired, processed and converted into actions depending on the familiarity with the situation is classified as an "Information processing" method. This model structure allows retrospective analysis to describe root causes of accidents which are believed to arise form an a lack of capacity to comprehend the situation. This classification of performance into categories based on operator training and familiarity with the situation was expressed in Rasmussens "skill-rule-knowledge" (SRK) framework (Rasmussen, 1983) , and further developed as more elaborate models which include an internal structure for human cognition. The ultimate result of these methods is to provide a model for the internal activities in the human operator between the "stimulus" and the "response".

The SRK framework prescribes different levels of performance depending on the load placed on the mental capabilities of the operator to observe, diagnose and execute the correct set of actions. In the SRK framework the number of performance shaping factors is reduced to one, the familiarity with the situation. It is important to note that there are several factors which can influence this familiarity (level of training, experience), but the performance of the human operator can be either aided or hindered by the lack of experience. The framework also place the mechanism of human performance in the mental capacity of the operator. A flowchart explaining the classification of activities into the performance categories can be seen in Figure 3.1.2.

Models of human cognition The stimulus-response model and the information processing model both share a passive trait. The models describe a sequence of steps in response to a external stimulus, and does not take into account any information seeking or anticipation by the operator. A sequence of processing steps may seem like a logical and ordered process in retrospective, but the future order of the processing stages are uncertain (Hollnagel, 1998). The unorderly sequence of the processing stages are capture in the "Simple model of cognition" (Hollnagel, 1998) seen in Figure 3.1.3. The simple model of cognition is a attempt to capture the relationship between the human operator and the

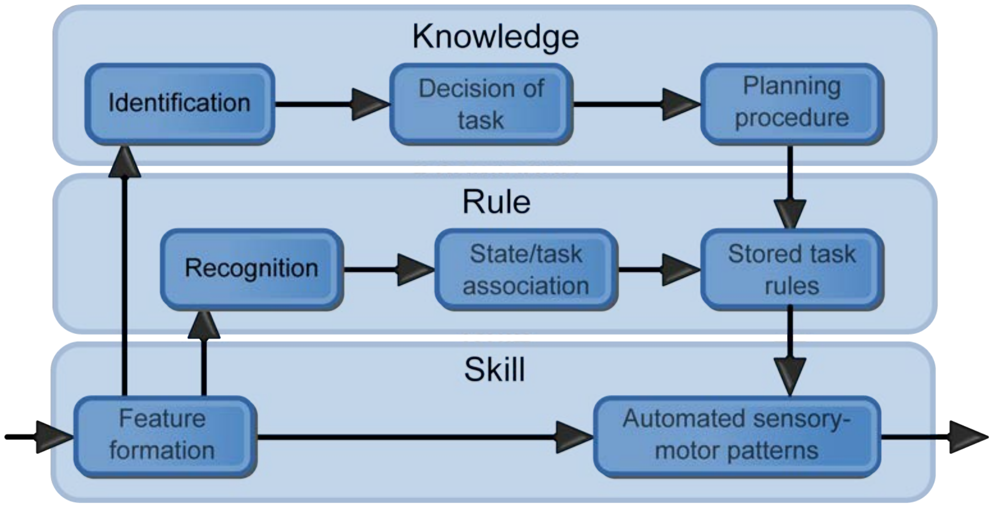


Figure 3.1.2: An depiction of an information processing model for human cognition. The "short circuit" paths corresponding to skill, rule and knowledge processing is superimposed.

system not as separate entities, but as continuously interacting systems. The operator and system are engaged in a continuous loop of anticipation-observation-action-observation where the operation does not passively respond to system events, but shares control of the system and acts in cooperation with the control systems (Hollnagel and Woods, 2005).

3.1.2 Summary

The distillation from human behavior to a single number influences the need for an explanatory model if the introduction of a model aggregation "anonymize" the human operator model with regard to the rest of the system. This anonymous human behavior can be seen as correct from the point of view of the mechanical system since the effect on the system is independent of the actual cause in the human operator after a set of actions has been completed. This relationship should be important for predictive analysis since this uncoupling removes the causal relationships from a single source to every source which could manifest itself in the same fashion.

This probability is tailored to the application of PSA and impose a binary output on the model as either "success" or "failure", but such a near-perfect relationship between two methods applied to engineering systems and to human behavior warrants further study. The underlying assumption of the information processing methods assume that the human brain functions in orderly fashion with information retrieval, information processing and a final hypothesis/decision stage. A failure of the human operator is conceptualized as a failure in the model stages leading to either wrong information being gathered, an erroneous conclusion or representation of the information and finally an erroneous decision based on the information. This orderly process is again appealing in the same way that

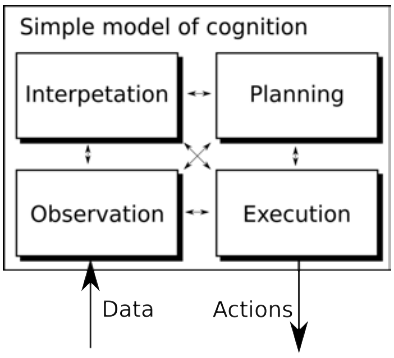


Figure 3.1.3: The simple model of cognition from (Hollnagel, 1998) which presents the human operator as an unordered sequence of observation, interpretation, planning and execution. The structure of the model is the most basic cognitive model available which still retain an internal structure, but without an implied sequence of the cognitive functions.

first order HRA methods are appealing form an FSA point of view. This orderly structure impose an unobservable ordering of the process which can be executed in any number of combinations. These combinations will appear orderly in retrospect, but from a given point in time, it is impossible to determine the process sequence a-priori. This orderly structure is therefore a feature of the model and not of the process. The correspondence between the underlying system (human operator) and the operator model must be considered before one can integrate a human operator model into a simulation model. This is necessary in order to ascertain the level of knowledge embedded in the model and if it can be expected that the model will provide a valid reproduction of the source system.

3.2 Modeling and simulation

The notion of a system, models and simulation are general terms which without proper definitions can lead to confusion by individual nuances and un-communicated assumptions about what is contained in the terms. There are several implicit, and to a lesser extend explicit, definitions of the word “system” and “model”. The framework from (Zeigler et al., 2000) is used to discuss modeling and simulation. The framework is detailed below and the terms and entities clarified from the definition of the interface between the studied components to the final description of a coupled system model with internal structure. The levels of system knowledge by (Zeigler et al., 2000) named “The levels of system specification” can be seen in Table 3.1 ordered by increasing knowledge about the behavior of the system.

Table 3.1: The levels of system specification presented with detail level in descending order

Level of system specification	Description
0	Input-output frame
1	Input-output relation
2	Input-output function
3	Input-output system
4	Structured input-output system
5	Structured coupled input-output system

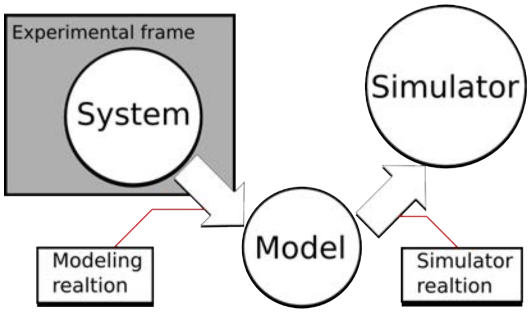


Figure 3.2.1: The relationship between a real-world system, the experimental frame, the model and the simulator.

3.2.1 Segments, the experimental frame and the input-output relation

Two basic terms of modeling and simulation must be defined before any elaboration on modeling of systems. The boundary between the system and the environment and an abstract signal type which can be used to describe the systems interaction with the environment. The environment and the interface between the modeled system and the environment is an experimental frame. The experimental frame can be seen as an additional system which is tightly coupled with the modeled system. The system and the experimental frame interact to produce the results of the simulation. The transmission of information between the experimental frame and the modeled system is called a segment. A segment is an signal which is a combination of one or more sequences selected from a pool of admissible sequences for input or output of the system.

The input-output relation is the correspondence between a single input segment, ω, and a number of possible output segments Y. This is a one-to-many relationship which only establishes the possible responses to a input segment, not a definite relationship which determines the actual response. The modeled component with only the input-output relationship specified can be illustrated with a hypothetical experiment of releasing a elastic ball and measuring its elevation above the ground. The input, or driving force, is gravity which is known as a constant force, the possible output segments of this constant force will depend on the unknown initial height and the rate of energy dissipation during the impact. The input-output relation will connect a given constant force with the numerous, or infinite, number of possible vertical position time histories depending on the unknown initial condition and elasticity of the ball.

3.2.2 The input-output functional relation

The functional input-output relation increases the knowledge level from the input-output relation. In the functional level the model is accompanied by an initial state which makes it possible to decode the-one-to-many property of the relation into a one-to-one map for the functional relationship. In the theoretical example of the bouncing ball, this would amount to knowledge about the initial vertical position of the ball which enables us to associate a particular output sequence with the input segment and an initial height. However the functional input-output relationship does not contain information about the internal mechanics of the model, it is merely an association between input and possible output via a initial value. In order to demonstrate knowledge of the model on the next level, the internal mechanics of the model must be known.

3.2.3 The input-output system

The progression in system knowledge from the one-to-one functional relation continues with the addition of an internal state, q, in the model. With this addition the model will fulfill the requirement of a self contained component capable of generating its own input-output behavior by expressing how the input influences the system state transitions $q_{k+1} = \Delta(\omega, q_k)$ and how the output, $Y_k = \Lambda(\omega, q_k)$, of the system is composed of a combination between the input segments and the internal state of the system. In the virtual experiment with the ball, the internal state could be the velocity of the ball in three dimensions. From Newton's 2. law we can establish the differential equation which links the input (external force) to the dynamics of the internal state. The output in form of the position of the ball can be established by a differential equation which relates the velocity and initial position to the final position of the ball.

The coupled and structured input-output system A structuring of the input-output system is a process that has analogies at the lower levels of model knowledge. The structuring of the system implies a structuring of the input & output segment and the internal state. The structuring can be seen as a first step towards a modular definition of systems. With a structured definition the interface between the model and the experimental frame becomes partitioned into sets corresponding to ports or slots which allow a certain variable with a certain range. Even though the system is structured there exists no formal way of representing the dependence and cross-coupling of the system state with the systems interface to the environment.

The coupled and structured input-output system represents the complete synthetic model of a real-world system. The addition of a coupling between the entities of the model constitutes the final level of information required to implement a fine grained representation. The coupling is another construct that relates the structure input to the structured state which specifies which parts of the systems state space are dependent on which inputs. In a similar fashion the coupling information also determines which parts of the system input and state space contribute to the parts of the structured system output. The coupling also enables a system model to be constructed by other system models by aggregating them with coupling information we can define new system boundaries and interconnections between system states and internal system components. The coupling process enables us to represent complex systems as a connected collection of hierarchical system which may contain subsystem.

3.2.4 Simplified systems and human operator models

To represent a system as a model one must construct a theoretical correspondence between the model and the system. To verify this correspondence one must ensure that the model and system are similar in a way that ensures that the model faithfully represents the system. This mechanism is the “morphism”, which can exist on all the levels of system specification as outlined in Table 3.1. A morphism on a given level also guarantees a morphism at a lower level. The morphism is a theoretical construct to ensure that a model, or simplified system, does not undergo state transitions which are not present in the original system and does not exhibit output behavior which is unobservable in the original system. The morphism is together with the levels of system specification an powerful tool used to assess the quality and correctness of derived models.

The morphism between a big (original) and a small (model) system is illustrated as a commutative diagram in Figure 3.2.2, where the functions g, h and k are appropriate translations between the two systems. The translation g between the input to the small and big systems ensures that input to the small system is also admissible input to the big system. The map k ensures that the output of the big system is a superset of the output of the small system. A morphism in the input-output system specification level must conform to a “transition function preservation” and a ”output function preservation”. The transition function preservation is the requirement that the state transition of the original system in response to the input to the simplified system is equal to the state transition in the simplified system if coded by the map h. The output function preservation requires the output of the simplified system with the state of the original coded by h is a subset of the output of the original system. This has two practical implications between a original system and a model

1. The model cannot exhibit state transitions not present in the original system.
2. The output of the model must be contained in the subset of outputs of the original system.

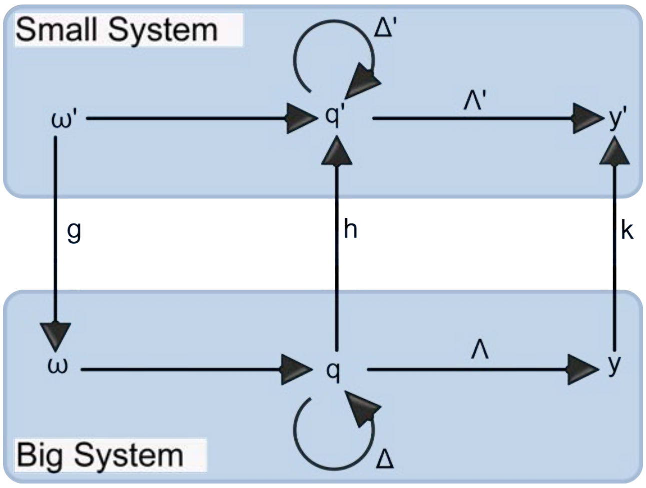


Figure 3.2.2: Commutative diagram which illustrates morphism relationships between a small and a large system with the different morphism elements illustrated

These requirements has implications on the use of human operator models in a simulation model of ship navigation and maneuvering. Due to the transition function preservation and the limited knowledge of the internal behavior of the human operator we cannot construct a morphism between an original system (human) and a full information processing or cognitive model. The simpler stimulus-observation-response models can be seen as a functional relationship, and particularly the S-R-K framework presents itself as a functional model.

3.3 A practical approach to include the human element in ship maneuvering simulations

An overview of the components in a complete model for ship maneuvering is seen in Figure 1.3.1 which shows a system comprised of the environment, mechanical components and human element. The mechanical components; the hull, steering gears, propellers and automation systems are well defined components which can be represented by first-principle models. These models are at the coupled-structured level of system specification and an accurate description of these system models can be constructed and coupled into arbitrary aggregate systems using a system-of-systems method. The inclusion of the human element in the form of a "planning-observation-execution" construct represents the full range of actions from the formulation of a voyage plan to the eventual manipulation of the handles on the vessel.

The mechanical components are suitable for representation in standard modeling environments since they can be represented in a closed form in the time-domain with well defined input and output interfaces. The reactive system model from (Zeigler et al., 2000) where the behavior is determined by the input forms the theoretical foundation of time-domain simulation technologies which is incompatible with the probabilistic and random-sequence formulations from human operator models. This is, at the minimum, a technological limitation which is encountered in attempts to integrate operator models with a simulation of ship maneuvering and navigation. The model type supported by modeling formalisms such as (Zeigler et al., 2000) is incompatible with the "second generation" human reliability methods of (Hollnagel and Woods, 2005; Hollnagel, 1998) due to the orderly execution the simulation models. The early human reliability models which represent the human element as a success-failure process without a specification of an underlying model for human performance can be considered for integration with simulation models. A simpler human reliability model can be used as a component of a larger model of the function of the human element in the ship navigation/maneuvering system.

3.3.1 A human element model for simulations

A simple human operator model can be used to represent a part of the function of the human element for navigation/maneuvering. The condensed schematic of Figure 1.3.1 include the three basic functions of the human element; plans, observation and execution. An operator focused decomposition of the human element is seen in Figure 3.3.2 where these functions are separated. The separation is a practical measure with the intent on reducing the complexity of the human operator representation by introducing assumptions and static representations of the functions. The structure is consistent with the three stage structure presented by (Chen and Stanney, 1999) to describe way-finding and is a combination of the following functions

Plan: A prepared strategy to take the vessel from A to B which includes detailed plans for confined waters.

Observation: Observation of the environment and monitoring the vessels progress and position is according to the plan.

Execution: Executing a particular short term planned maneuver such as maintaining course by manipulating the rudder or ensuring that a navigational marker maintains its bearing.

The separation is dependent on the assumption that there is a well prepared plan which can be treated as a static entity and that the operator is competent in executing the intended actions. Competence of the operator is represented by an automatic control formulation of basic maneuver types and the deterministic function of an control algorithm. A static plan can be estimated by the method of Chapter 2 and this leaves observation, and implicit decisions, as the area of the human operator which must be addressed in order to represent this view of the human element in a simulation.

Plan Piloting a ship is a complex task where passage plans are constructed by the master before any significant voyage. The plan outlines the ships preferred path, and in confined waters, prescribe the geometric properties of the planned path. (Lützhöft and Nyce, 2006) described the training of certified pilots for the Stockholm archipelago which included creation of a personal preferred passage plan of the area and a similar concept of standard practices and a-priori planning is found in (Gould et al., 2009). The passage plan was described in detail by (Lützhöft and Nyce, 2006) as an interconnected sequence of straight course lines and circular turns with the following properties

Straight course line: Course lines with notes for both in-bound and out-bound course angles

Circular connecting sections: The radius of the turn was noted together with land marks or navigational markings and their bearing to determine when to initiate a course change.

The planning process as described by (Lützhöft and Nyce, 2006) includes reference to both the environment in the form of landmarks, navigational markings and references to a set of basic maneuvers used to traverse the plan. This description motivated the formulation of the previously mentioned "simple traffic model" and the output of the traffic analysis can be used as input for the plan representation during simulations. This formulation is extendible as it allows new maneuver types to be available during maneuvering by implementing a suitable autopilot and referencing them in the plan.

Observation Observation of the vessels position and relative orientation to landmarks on a modern bridge is a dual-process which involves both electronic navigation systems and visual observation. Bridge systems have undergone a dramatic development form observation decks with communications to the engine room and wheelhouse to a integrated command and control center (Lazet and Walraven, 1971). Electronic navigation systems such as GPS and the former Loran C has long been used to obtain a position fix for the vessel, but the orientation of the vessel relative to the environment is still verified visually by means of landmarks and navigational markers. While electronic chart display and voyage planning systems are installed on most bridges, observation of the environment by radar, and visually (when possible) is still an integral part of bridge procedures. Over reliance and misplaced confidence in the electronic positioning systems has lead to accidents as by (Lützhöft and Dekker, 2002) in a case study of the ROYAL MAJESTY where a malfunctioning electronic navigation system combined with incorrect visual confirmation of navigation markers led to the grounding of the vessel. The reliance on visual observation is emphasized by the prominent presentation of navigational aids on electronic chart systems, and ensures an continuous involvement of the bridge personal while navigating confined and congested waters.

Execution The execution of individual maneuvers is performed in a tight loop with continuous observation of the properties of the ship and the environment. The continuous manipulation of the vessel is reminiscent of an automatic control algorithm, and did inspire the first course autopilot for ships (Fossen, 2002). Manual control and autopilots has a symbiotic relationship where the autopilot will translate the operators intentions into actuator actions as in thrust allocation by DP-control systems, and the manipulation of course autopilot settings (Accident Investigation Board Norway and The Bahamas Maritime Authority, 2010) instead of the rudder. The human operator and the high level control system becomes indistinguishable from the view of the vessels low-level actuator systems.

3.3.2 Time domain simulations of maneuvering with the human element

The simulation model used in (Aarsæther and Moan, 2010) is an application of the decomposed human element model presented in the previous section and is illustrated by Figure 3.3.2. The simulation model consists of environment and ship dynamics in addition to separate plan, observation/decision and execution sub-models. An environment representation for simulations of ship maneuvering includes the forces from wind, waves and current, which represent the impact of the environment on dynamics of the vessel. If the representation of the environment is to be considered as an experimental frame for the vessel it will need to include the navigational markers. The navigational markers are an important part of the environment during navigation and maneuvering, and an experimental frame which is expected to accommodate a simulation model of this process must include both the effects of the environment on the dynamics and the connection between the navigator and the environment.

A simulation model of the dynamic behavior of the ship responsible for replicating the behavior of actual vessels in response to the actuators and the environment. The underlying dynamic model of the vessel must model both the rudder and the engine as they are the main actuators used during maneuvering. The model used in the simulation examples in (Aarsæther and Moan, 2010) is the maneuvering model of tankers from (van Berlekom and Goddard, 1972). This model was preferred due to the included models for main engines, main propellers and the availability of parameter sets for vessels ranging from 20 000 DWT to 500 000 DWT. This eases calculations, but it does lack the sophistication of system simulators which represent the interconnected support systems of the vessel by separate models. The model of (van Berlekom and Goddard, 1972) is a model of the ship dynamics in the horizontal plane derived from experiments and in addition to the rudder and main propeller models consists of a rigid body model together with approximate expressions for the hydrodynamic forces during maneuvering. The model is an simplification of a full six degrees of freedom dynamic model with internal state on an a priori known form. A reduced state space model from experiments is an manifestation of a morphism in the sense of (Zeigler et al., 2000) since the permissible inputs to the model is also permissible inputs to the real system (engine and rudder commands), the transition function preservation is fulfilled since the state transition in the model of the full system states translated to the model will correspond to the same state transition of the reduced state set in the original. This leads to an output which is also present in the original system

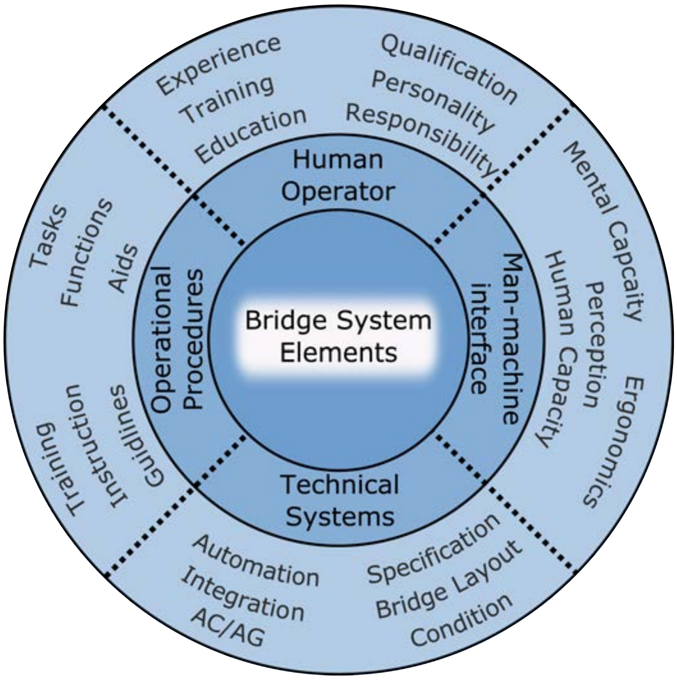


Figure 3.3.1: The elements present on the bridge of a vessel. The systems include the human operator(s), the organization in the form of procedures and the technical systems and their interface.

(output function preservation) which should be expected since the reduced order model of the ship is an projection of the original system onto the horizontal plane.

The plan of passage is in the simulation model represented as a static entity which is accessible from the representation of the human operator. The plan is a collection of maneuvers in sequence, where the transitions between the maneuvers are specified as conditions dependent on the navigational markers in the area. Each maneuver type correspond to a basic maneuver type used during navigation from the previously mentioned simple traffic model. The presence of external references in the plan makes it possible to determine if the vessel should transition to a new maneuver by comparing the contents of the plan to the environment.

Vessel guidance is achieved by constructing a set of autopilots for each maneuver type required by the plan. The autopilots can be readily constructed by constructing different reference trajectory generators and suitable reference tracking algorithms. The combination of the parameterized maneuvers in the plan and the observation of the vessels position determines which autopilot is activated and the parameters used to control the vessel. The selection of different autopilots for different control strategies is a manifestation of the supervisory control paradigm.

Completion of a decomposed human element model as presented previously with an observation-decision model is dependent on the experimental frame which is used to accommodate the model. The navigator observes the environment through the naviga-

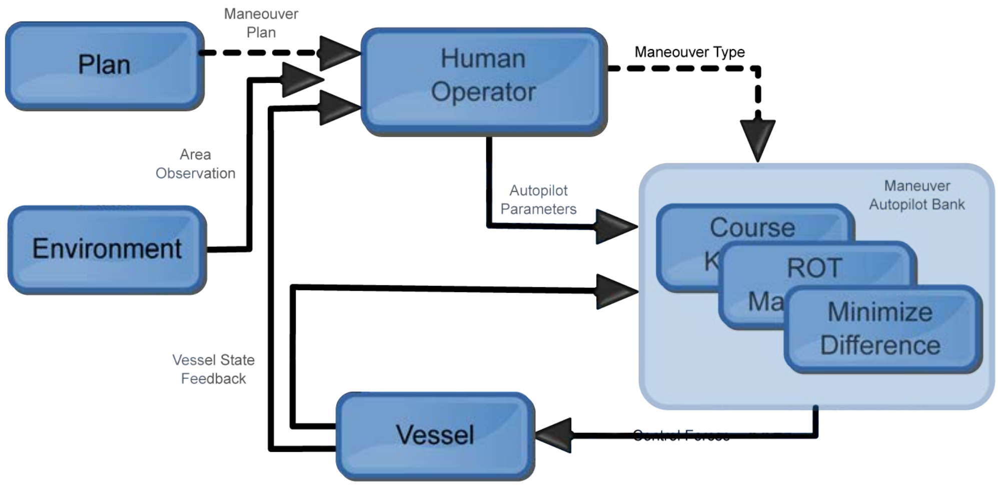
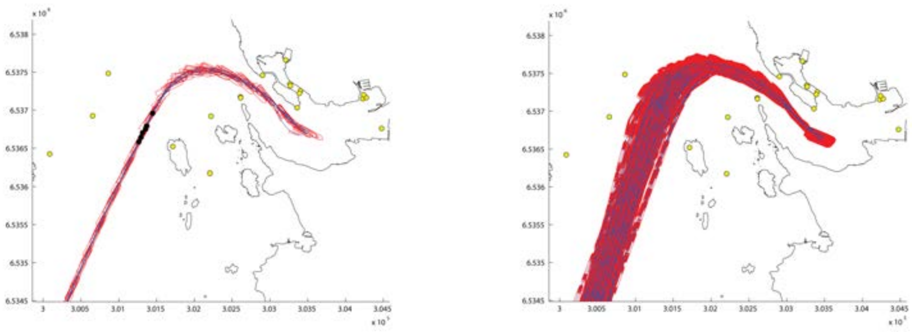


Figure 3.3.2: The proposed simulation model for a single vessel where the human operator is decomposed into three functions; planning, observation and execution.

tional markers but this still leaves the internal dynamics of the team on the bridge, and the interaction between the human operators and the technical systems on the vessel. Organizational factors and training increase the complexity of the interaction between different actors in the total bridge "system". The factors which influence the working conditions of the bridge team is shown in Figure 3.3.1 where influences ranging from organizational factors to human-machine-interaction are presented. Attempting to construct a detailed model of the bridge is unwise in light of the internal complexities of the internal and external system interactions and the requirements for constructing a detailed model with internal state. The requirements associated with a system (internal state) morphism of the bridge system is currently insurmountable and the only level of system knowledge which can be represented during a simulation is, at this time, the functional level. This implies that models of human performance should be able to reproduce past observed performance during simulations. This implies that the simulation model is then incapable of eliciting new information about human performance, but sufficient to analyze the system dynamics in response to known human performance levels. The functional level of system knowledge is embodied in curves derived from experiments where an initial state or system property is used to distinguish the different output behaviors in relation to the corresponding inputs, the skill-rule-knowledge framework of Rasmussen is an example of a model. The skill-rule-knowledge model is sufficient in order to represent the level of performance for the total bridge system, since the complexities of the system makes it difficult to accurately represent the relationship between the influencing performance factors. The time response curves for the skill-rule-knowledge framework from (Hannaman and Worledge, 1988) makes the framework a suitable starting point of integrating a human element model with time-domain simulation. The observation-decision sub-model was implemented by continuously evaluating the position of the vessel in relationship to the environment and the current plan. The transition time between two maneuvers was then derived from the response curves of (Hannaman and Worledge, 1988) in combination



(a) Simulations of ship maneuvering with decomposed human operator model. The figure shows the results of maneuvering 9 different ship dynamics with identical plans. Time of turn initiation is shown as black dots.

(b) Simulations of ship traffic with a single ship dynamic. All simulations with the same navigational plan and initial state of the vessels were drawn from statistical distributions estimated to accompany the simple traffic model.

Figure 3.3.3: Simulations of ship maneuvering with navigation provided by the decomposed human operator model.

with the vessels response time to rudder inputs represented the time spend deciding if the condition required to execute the next maneuver was fulfilled.

3.3.3 Simulation results

The simulation model was tested by a simulation series with differing ship dynamics, initial state and with one of the estimated navigational plans in (Aarsæther and Moan, 2009b) as input. The observation model included an anticipation about future position and orientation of the vessel based on the “advance” of the vessel dynamics from the standard IMO turning circle trials. The supervisory control formulation was successful in controlling the vessel along the intended path as seen in Figure 3.3.3a and Figure 3.3.3b. The guidance and navigation mechanism behind the vessel trajectories are an implementation of the decomposed human operator model and reacts to the relative placement of the vessel in the environment. The simulation model also exhibited the expected behavior in response to the adoption of either skill, rule or knowledge based processing as seen in (Aarsæther and Moan, 2010).

Chapter 4

Conclusions and recommendations for future work

4.1 Summary and contributions

This thesis deals with analysis of collision and grounding by considering frequency estimation of ship traffic. New methods for use in analysis either by simulation or observation are presented. It has been shown how analysis for quantification of marine traffic in the form of the distribution of vessels, speeds and arrival times can be aided by the AIS analysis techniques developed as a part of this thesis. The thesis also highlights deficiencies in simulation studies of marine traffic where the human operator is neglected and that the present development of human operator models for risk analysis does not contain the required model sophistication for inclusion in a time-domain simulation. This is not a critique, but rather an observation about the current state of knowledge about human operator modeling. A practical approach for including a less sophisticated human operator model was developed by decomposing the operator and supporting systems into the trifecta of planning, observation and execution.

4.1.1 Contributions

This thesis has contributed by developing analysis methods for use both with observations and simulations. The original contributions in this thesis can be separated into contributions to analysis by observation and analysis by simulation.

Contributions to analysis by observation

A simplified model for ship traffic and navigation The simple traffic model was presented as an prerequisite for analysis to relate the measurements to an idealized case. The model is also useful to implement navigation in simulation models.

An analysis method for large volumes ship traffic data from AIS Image analysis has not previously been applied to the problem of analyzing ship traffic and it has been presented in this thesis as a solution to the large quantities of data produced by AIS. The image analysis technique also enables automatic discovery of maneuvering patterns and aggregation of consistent data for further analysis of marine traffic.

A method for generating approximate navigational plans The combination of the simple traffic model together with analysis results of the AIS data and navigational markers has generated approximate navigational plans. These plans can be used as an input to simulation studies in order to define a operating scenario.

Contributions to analysis by simulation

System theoretic discussion of human element models Human operator and time-domain mechanical systems are incompatible and at the same time required in order to represent the complete system. The theoretical relationship between the human operator and the mechanical systems has been explored and shown that the combination is currently only capable of capturing replicative behavior of the human operator model.

Human element in autonomous maneuvering simulations An model based on the separation of planning, observation and execution has been proposed which reduces the complexity of the human operator model with a static representation of plan and intentions.

4.2 Conclusion

This thesis has shown AIS is a valuable source of data for ship traffic analysis and not only as a real-time information system. The usefulness of AIS becomes apparent when the high-volume information stream is combined with an analysis technique which offloads repetitive and time-consuming processing to an automated process. Image analysis has been shown to be an capable approach to automated analysis and grouping of AIS data into traffic-patterns defined by geometry. Image analysis has also been used to map the maneuvers of an aggregated traffic-pattern to regions of individual AIS data sets. The current level of human reliability models, while full featured for retrospective analysis and predictive analysis in the frequency domain, are insufficient to properly capture the dynamics of human performance required for simulations in the time-domain. The only realistic method to include the human operator in a time-domain simulation has been shown to be either with human-in-the-loop simulations or by the use of response curves which are of only reproductive ability. Response curves can be integrated with time-domain simulations as demonstrated in this thesis, and even if the human operator model contains only replicative abilities, the full simulation model presents a more complete system model than application of typical waypoint guidance algorithms form automatic control.

4.3 Future work

The most apparent opportunity to extend the work presented in this thesis is to combine the analysis method of ship traffic with a more complete set of data sources such as bottom topography and meteorological data. A combination of marine traffic analysis with topographic and meteorological data is a first step towards analysis and assessment of grounding in risk analysis.

Future work built upon the foundation laid by this thesis can be divided into two classes; method development in AIS analysis and simulations or application of the method in risk analysis. The analysis of the AIS data can be improved by introducing more sophisticated image analysis techniques which could account for the slight variations in shape among vessel tracks by employing an analysis model where the observed vessel tracks are distortions of an underlying prototypical shape. This would further increase the confidence in the automatic aggregation of vessel track-lines. There is obviously an opportunity to use the presented methods for quantification of frequency in a larger, or more complete, risk analysis. The traffic model can, in both observation and simulation, be combined with bottom topology which could serve as an intermediate to prediction of grounding.

There are also opportunities for research on how AIS data is coded for long-term storage. The present state of long-term storage in Norway is to keep the raw AIS data for 2 years before down-sampling it to a resolution which makes it useless for navigation and maneuvering analysis. This down-sampling has an amnesia effect on the data available from the AIS operators, as we could lose the opportunity to study changes in the navigational patterns which occurs over periods of more than 2 years[1]. A more efficient method for storing the data of the dynamic AIS messages could enable both storage of long term AIS data with documented representation accuracy and ease the derivation of statistics as an more efficient and idealized method would probably ease the processing of data.

The use of human operator models in simulations of marine traffic is in need of research since the problem is integral to the continued use of time-domain simulations in risk analysis of marine traffic. The research should be focused either on deriving marine traffic specific operator curves mirroring the developed response curves in (Hannaman and Worledge, 1988) for operation of vessels. Both models exhibiting functional replicability and detailed base models specific for the marine environment would be a welcome development, but detailed models should be suitable for both retrospective and predictive analysis in the time domain as a detailed model must be able to serve as both a reference for analysis and prediction if observations are to be obtained for use in prediction.

[1]The time window is probably less due to transient effects which one would expect from construction activities related to changes in the fairway.

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Appendix A

Published papers

A.1 Thesis papers

Autonomous Traffic Model for Ship Maneuvering Simulations Based on Historical Data

Published in the proceedings of the 7th international conference on computers applications and information technologies in the maritime industries (COMPIT 08)

Autonomous Traffic Model for Ship Maneuvering Simulations Based on Historical Data

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Abstract

Computer simulation is frequently used in the assessment of human performance, training and risk analysis of ship maneuvering. An important component in such simulations is the surrounding environment, including both weather and traffic. Weather is often represented by time-domain realizations of meteorological data. We present a similar approach to modelling traffic lanes in an area, using data gathered from Automatic Identification System. The main contributions in this paper are (i) a model for dynamic ship traffic in an area guided by the IMO "International Regulations for Preventing Collisions at Sea", and (ii) a method for calculation of the location and statistics of the main traffic lanes from a real-world area. The presented model can readily be integrated into ship maneuvering simulation environments and used as a time-domain traffic representation. The presented procedure groups 3200 AIS time-series into 5 main traffic-lanes

1. Introduction

Ship maneuvering simulations have gained acceptance as a tool for risk analysis, autopilot development and crew training. Simulations are often focused on the interaction between the local ship and the natural environment and great effort has been devoted to the development of accurate models for ship dynamics e.g. *Berlekom* (1972) and *Fossen* (2002,2005). The environment in a ship maneuvering simulation is composed both of the weather conditions and the instantaneous traffic situation. Weather models are available from statistics meticulously gathered for decades and allow us to represent visibility, waves, wind speed and direction with time domain realizations. There are no comparable sources for description of ship traffic. The ever-increasing power of computers has made high complexity Mote-Carlo type studies feasible, and it has become possible to experiment with several ships in the same simulation. In past traffic simulation studies the navigation interaction between the local ship and other vessels have been simplified away in *Hutchinson* (2003) or ignored and replaced by "blind navigation" models, which ignore all navigation interaction in *Gucma* (2007) and *Merrick et al. (2003).* The overall ship traffic in an area is composed of vessels following different traffic lanes, each lane with different characteristics such as traffic density, points of origin and destination, speed, cross-track spread and course changes according to a predetermined program. A model for the traffic situation in an area would complement weather models and forms a more complete description of the maneuvering environment.

Description of the geometric traffic features as well as quantification of variability in the traffic pattern has been in the domain of expert opinion, but the introduction of the Automatic Identification System (AIS) has, as a secondary effect, enabled mass collection of quantitative data of ship traffic. Data available from AIS can be used to construct ship track-lines and process these to obtain the geometric description of the traffic pattern and its dynamic variation in ship speed and cross-track error. In this context three separate definitions of traffic data is needed

- Time-series: Time ordered data of the state of a single ship
- Track-line: The trace of the ship position over time
- Traffic-lane: A collection of track-lines following a similar path

Traffic density on a traffic-lane can be measured by the arrival times of vessels. Inter-arrival time statistics can be determined and applied to represent the appearance of new vessels at the start of the traffic-lane. To explore the capabilities of traffic-lane modelling from AIS data the area around the harbour of Tananger on the southwest cost of Norway was selected. The area was selected due to availability of AIS data, constricted waters, which should give a well-defined traffic pattern, and the presence of arriving, departing and passing traffic. The area along with AIS position reports from traffic is seen in Fig.1. The traffic-lane statistics can be of value in itself, as it allows us to analyse the current traffic pattern in the form of preferred paths, traffic density and the spread of traffic along the paths. Traffic-lane statistics also provide an desired track and "real-world" variation of initial conditions for maneuvering simulations, and can be used in training simulators to provide a dynamic environment.

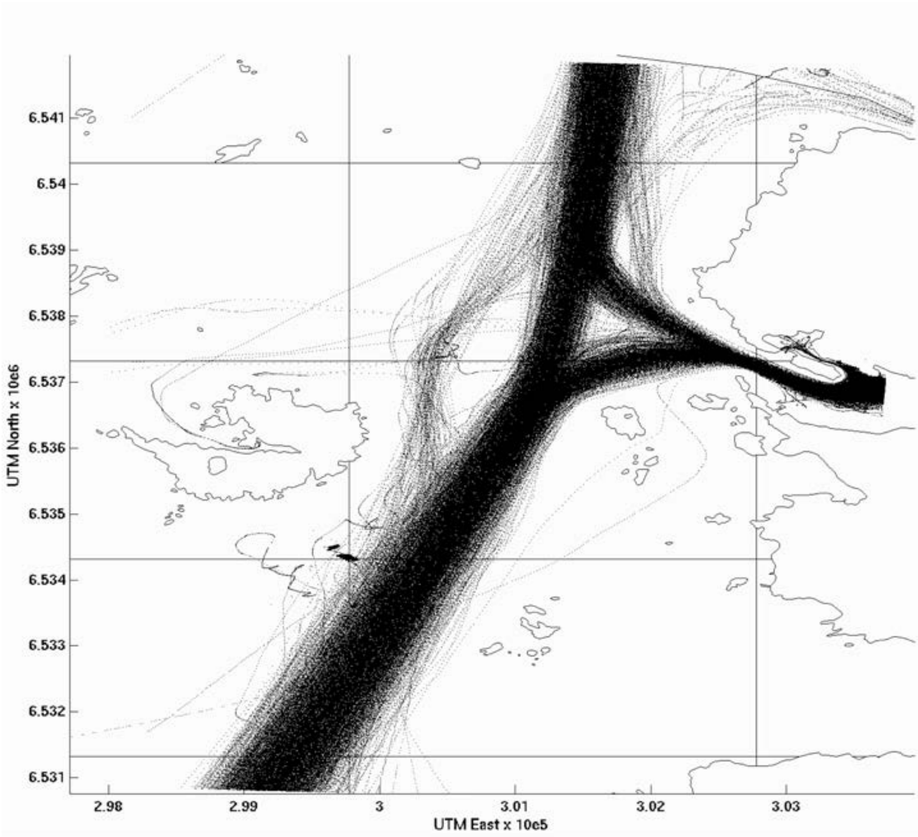

Fig.1: Studied area with AIS positions from three months

2. Ship Traffic Data and The Automatic Identification System

AIS has been introduced through the IMO convention "International Convention for Safety of Life at Sea" (SOLAS), and is in various stages of completion in costal nations around the world. The Norwegian AIS system became fully operational in 2007. The AIS system is a transponder-based system where each ship broadcasts both variable data such as instantaneous position, speed and time and voyage specific data such as origin, destination and type of cargo. Every message is marked with the time of transmission and a unique identification number, the MMSI number, assigned to the vessel by The International Telecommunications Union. The variable position data is transmitted at varying intervals depending on the ship's speed and maneuvering situation, the sample rate in different conditions is shown in Table I. The sample rate may be lower in congested waters as the communications channel is shared and has finite bandwidth.

2.1. Data Collection

Data is continuously collected by AIS base stations and is available in full resolution for some time before it is converted to a lower resolution format for long-term storage. The Norwegian Costal Authority made full resolution data from the larger area around Stavanger for the second quarter of 2006 available for research upon request. This data was in the form of data-frames as received by the AIS base stations with time, MMSI number, latitude, longitude, course over ground, speed over ground and rate of turn. The position and speed data transmitted is collected from the ship's GPS receiver.

Table I: Sample Rate of Variable Data from AIS *IMO (1974)*

Maneuvering Situation	Sample Rate
At anchor	3 min
Speed 0-14 knots	12 s
Speed 0-14 knots and Changing Course	4 s
Speed 14-23 knots	6 s
Speed 14-23 knots and Changing Course	2 s
Speed > 23 knots	3 s
Speed > 23 knots and Changing Course	2 s

2.2. Time-Series Construction

AIS broadcasts have no sequence number and the data must be processed to form time series suitable for traffic analysis. The samples were restricted to be within the area of interest, and ordered by time and MMSI number. This resulted in time-series of the variables by ship number but with significant discontinuities when the AIS transponder left the area of interest, or ceased transmission and reappeared at different position. This behaviour results in significant discontinuities in the time axis and the data was partitioned further at these discontinuities. Due to the inherent variability of sample rates in the AIS system the check for time discontinuities is non-trivial. Computing the mean μ_{time} and standard deviation σ_{time}, of the sample rate and checking for time differences larger than $\mu_{time}+\sigma_{time}$ deviation was used to detect the discontinuities. To account for the situation where a vessel might come to rest for a significant time, position reports with zero speed were removed.

3. Time-Series Processing

The time-series representations of the traffic in the area were grouped to form the foundation for the traffic-lanes. A property of the traffic-lane is the prototypical plan of maneuvering which the ships master will follow to traverse the area in a controlled fashion. In *Lüthöft* (2006) and *Aarsæther* (2007) the passage plan of master operating in constricted waters is presented as a set of course lines connected by tangential circles of known radius. This representation was chosen to represent the geometry of the traffic-lanes in the area.

3.1 Grouping of Time-Series

The track-lines from the time-series construction has non-uniform sample rate and speed, this complicates grouping since there is no fixed relationship between the data-frames in different time-series. Track-lines were grouped by considering their geometric properties in the form of a "track-line image". The area was divided into 50m-by-50m boxes and the number of data frames in each box was counted for each track-line. The result was a matrix representing the position report density. This matrix can be interpreted as a low-resolution image of the track with each box representing a pixel. This approach has several advantages for construction of track-line groups:

- Low sensitivity to variable speed and variable sample-rate
- Not dependent on knowledge of entry and exit points
- No assumptions of path start and end point location at the edges of the area

Track images were grouped by considering the number of side crossings and comparison of the track image differences. All track-images had the same resolution and orientation, which simplified image comparison. The processing exaggerated the track images by growing the track image from each sample the equivalent of 75 m in each direction by considering sections adjacent to samples to also contain samples. The exaggeration preserves the shape of the track and eases comparison of tracks of similar geometry, but with a slight offset. The process of exaggeration and its result compared to a regular comparison is shown in Fig.2. Sections with samples are shown as white (images are 90° rotated due to different axis conventions in image processing). To test whether two track-lines were similar the track-images were converted to a matrix of values 1 and 0, where 1 denoted the presence, and 0 the absence, of samples in a box. The track-images were then subtracted from each other to test for similarity. The success criterion was based on the ratio of non-zero section after the subtraction compared to the two original images. If the number of non-zero pixels in the result was less than 50% of the number of non-zero in each of the original images, the tracks were marked as equal. The track pair in Fig.2 was determined to be equal.

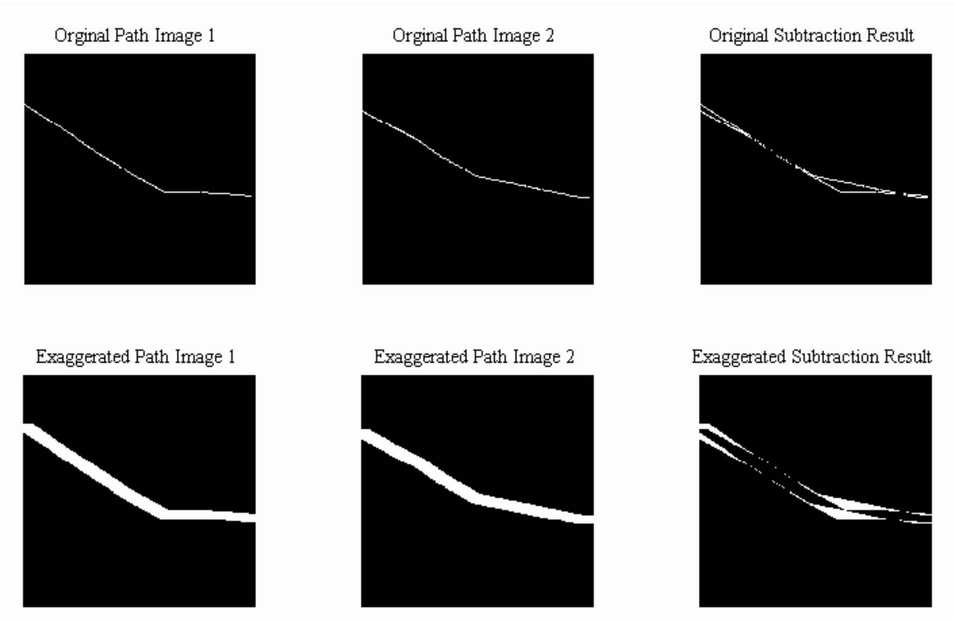

Fig.2: Path Match Results With Original and Exaggerated Track Images

Using an initial track image as reference, the remaining time-series where grouped with it if the track-image was indentified as similar. This process was repeated until all of the time-series belonged to a group. The end result was inspected by an operator and allowed the operator to mark different groups as being representative of the same traffic-lane, and to remove groups consisting of stationary points.

3.2 Traffic Lane Construction from Time-Series Group

The track-lines from the grouped time-series were used to compute geometry and variability of the group's traffic-lane. The model for the traffic-lane was a set of straight sections connected by tangential circles, each section with associated statistics for cross-track spread and speed. The grouped time series was first split into two groups by considering the direction of the start and end points. The mean track-line was calculated by finding the mean points along 100 partitions of each time-series. The partition of each time-series was calculated by finding the points on the track-line corresponding to 10% increments of the track total length. The mean position along with the mean perpendicular line at each partition was computed and taken as the mean track-line. The curvature of the time series was computed to separate the mean track-line into straight and circular sections.

3.2.1 Curvature Calculation

The curvature κ of the track-line can be calculated from the position and time data. This can be achieved by filtering the position data to remove noise and then use a numerical expression for the curvature calculated by solving the equation for a circle passing through the three consecutive points. κ can also computed be directly from the time domain signals for the position $x=x(t)$ and $y=y(t)$. The curvature of these two signals in Cartesian coordinates with ϕ as the tangential angle of the signal.

$$\kappa = \frac{d\phi}{ds} = \frac{d\phi / dt}{ds / dt} \tag{1}$$

$$\kappa = \frac{d\phi / dt}{\sqrt{(dx/dt)^2 + (dy/dt)^2}} = \frac{d\phi / dt}{\sqrt{\dot{x}^2 + \dot{y}^2}} \tag{2}$$

The need for *dϕ/dt* can be eliminated by the following identity

$$\tan\phi = \frac{dy}{dx} = \frac{dy/dt}{dx/dt} \tag{3}$$

$$\frac{d\phi}{dt} = \frac{1}{\sec^2\phi}\frac{d}{dt}(\tan\phi) \tag{4}$$

$$\frac{d\phi}{dt} = \frac{1}{1+\tan^2\phi}\frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\dot{x}^2} \tag{5}$$

Equation (5) substituted into Equation (2) gives the final expression for the curvature

$$\kappa = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{(\dot{x}^2 + \dot{y}^2)^{3/2}} \tag{6}$$

This expression for κ relies on the derivative and double derivative of the vessel track-line positions. Numerical calculation of these derivatives from noisy position data is inherently error prone. Instead of calculating the derivatives numerically, the derivatives are evaluated by fitting polynomials to the *x(t)* and *y(t)* signals. It is impossible to find a general polynomial to describe the complete track with sufficient accuracy for the entire ship track. To calculate the curvature at a specific track sample, a 5th order polynomial is fitted at a section spanning 20 samples both forward and backward in time. This provides both a theoretical form for the evaluation of the derivatives and suppresses the noise in the positioning data. The derivatives and double derivatives can then easily be evaluated from the corresponding formulas for polynomials. The polynomial fit was computed using MATLAB's 'polyfit' function using both centering and scaling to improve the numerical properties of the fitting procedure.

3.2.1 Connection of Traffic Lane Sections

The mean track-line was converted to traffic lane sections by considering the mean value of the group track's curvature at the partitions. The mean, μ_κ, and standard deviation, σ_κ, of κ along the mean track was calculated. Turn sections were identified as sections where κ was outside the band defined by $\mu_\kappa \pm \sigma_\kappa$. If the section was identified as a turn, the curvature of the section was associated with it for later reference. The mean value of the curvature, $\mu_{\kappa\,\mathrm{sec}}$, of the turn sections connecting two straight sections was applied to fit tangential circles as a connection. The tangential circles were placed with $r = 1/|\mu_{\kappa\,\mathrm{sec}}|$, the center of the circle is computed as the intersection between the straight sections with a perpendicular offset *r* in the turn direction. The straight and circular sections had their end points altered to coincide with the intersection between the lines and the circle. An illustration of the procedure is seen in Fig.3. For curved sections at the start or end of the traffic-lane the tangential circle was placed to intersect the adjacent straight line and pass through the border point at the angle formed by the line from the point to the end of the straight line.

The intersection point of the circle and the line is not guaranteed to fall within the end points of the line. If the end of the circle section was past the end of the line in the traffic direction, the line was removed and the circle was fitted again to the new adjacent segment. Special care was taken when two circular sections became adjacent to make the transition between circles smooth.

- If two adjacent circle segments had the same turn direction, they were merged, and a new tangential circle was fitted to the adjacent sections
- If two adjacent circles had opposite turn directions, the two circle centres and the transition point between them were required to be on the same line. To ensure an equal course at the transition point and thus a smooth transition between the curved tracks

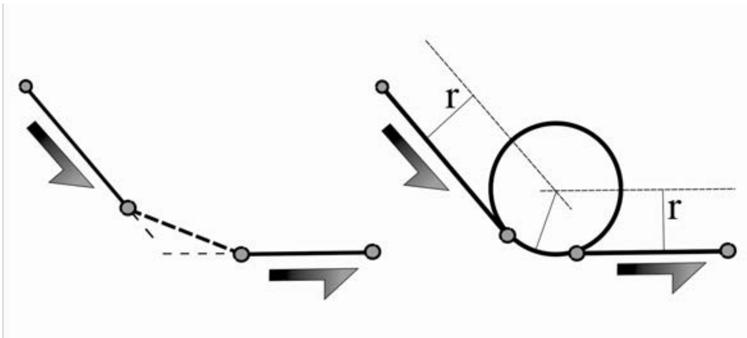

Fig.3: Placement of Tangential Circle Traffic Direction Indicated by Arrows

After the mean track-line was transformed to a list of straight lines and tangent circles, with the final end points of the sections determined, the statistics for cross track deviation and speed for the sections were updated to reflect the changed section boundaries. The inter-arrival time of ships was also computed and associated with each traffic lane.

3.3 Area Model

The directional groups in the traffic lane model described in Section 3.2 are treated as separate traffic lanes. The traffic in the area is modeled as a set of traffic lanes belonging to the area with associated statistics of inter arrival times, speed and cross track spread. The statistics for speed and cross-track spread are distinct for each section in a traffic lane while the inter arrival times are a property of the traffic lane as a whole. The arrival of traffic on each traffic lane is modeled as a queue and ships arrived at the start points following a Poisson process. The inter-arrival time is found from the first sample in each time series grouped to from the foundation for the traffic lane. The cross-track spread is assumed to be normal distributed about a mean cross-track deviation.

4. Ship Model

The most significant contributor to variability in the spatial properties of ship traffic is the actions of the master and navigation plan. The ship model used was a simple 3 degree-of-freedom model with simple dynamics in rotation and forward speed. The lateral speed is modeled as a dependent variable of the rate of turn. The purpose of this model is to provide a dynamic object for traffic simulations and not to give an accurate description of ship dynamics. More accurate dynamic ship models have been described in e.g. by *Fossen* (2005, 2002). The ship model assumes that the navigation is a process where the difference between a desired and actual value of a maneuvering parameter is minimized. The ship model is guided by two autopilots

- Course keeping autopilot, minimizes the difference between actual and desired course
- Turn Circle Autopilot, minimizes the difference between forward speed divided by desired turning circle radius and the rate-of-turn (Aarsæther 2007)

Each ship is associated with a traffic lane model and navigates the path by following the course of a path segment a distance equal to the length of the section. Course changes are executed as a circular path of known diameter until the course is changed to the course of the next section.

4.1. Dynamic Model

The dynamic model of the ship movement is a simple first order model where the accelerations are directly proportional to the deviation between the current and desired speed. The dynamic model was controlled by a Proportional-Integral feedback of the course angle when following a straight section and a proportional feedback of the rate-of-turn when changing course. The simple structure of the dynamic model is described by Equations 7 to 9.

$$\dot{u} = (u - u_{desired}) \cdot T_u \tag{7}$$

$$\dot{v} = r \cdot T_{vr} \tag{8}$$

$$\dot{r} = (r - r_{desired}) \cdot T_r \tag{9}$$

u_d is the desired speed and taken as the current track section speed. r_d is computed in the autopilot and dependent on the maneuvering mode, which is derived from the current section type. If the current section is a straight line r_d is computed from Equation (10) with $\Psi_{desired}$ as the current section course. If the current section is a course change section then r_d is computed from Equation (11) with R_{turn} as the radius of the turn.

$$r_d = -r \cdot K_p + (\Psi_{desired} - \psi) \cdot K_i \tag{10}$$

$$r_d = \frac{u}{R_{turn}} \tag{11}$$

4.2. Collision Avoidance

When traversing a traffic lane the ship models may enter the proximity of other ships, and in turn alter the navigation situation. This interaction can be harmless, or the ships can interfere with the safe passage of other ships. If the ship could interfere with the safe navigation of others, actions must be taken to prevent the occurrence of an unsafe situation. In IMO (1972) appropriate actions for shipmasters are given for the three interaction situations. Appropriate responses are given in Table II where "Ship I" is encountering head on, overtaking or crossing the path of "Ship II"

Table II: Interaction Type and Appropriate Response IMO (1972)

Interaction Type	**Ship I response**	**Ship II response**
Head On	Alter Course Starboard	Alter Course Starboard
Overtaking	Do not Interfere with Ship II	Continue
Crossing	Alter Course, Preferably Cross Behind Ship II	Continue

It is also stated in IMO (1972) that action taken should be of a magnitude evident to the other ship. *Cockcroft and Lameijer* (2004) advise against using speed control to avoid unsafe situations, as it is difficult to detect from the bridge of the other ship. This interaction between ships was modeled by introducing logic in the autopilot that checked for proximity of other ships and if other ships are present calculates:

- The encounter situation type; head on, overtaking or crossing
- Should this vessel "stand on" or "give way" in this interaction
- Time to Closest Point of Approach (TCPA)

- Distance at Closest Point of Approach (DCPA)

If the distance between two ships is less than 2 km they are assumed to interact and TCPA and DCPA is computed for the current state. If TCPA is negative (closest point of approach is in the past) or DCPA is larger than a given safety distance, no action is taken. Otherwise the ship that is to give way tests alternative course angles and cross-track offset until a acceptable solution is found. This solution is added as a desired offset in the navigation plan and removed when the interaction ceases.

5. Results

Processing of AIS data to obtain the traffic lanes and associated statistics was implemented in MATLAB. The AIS data was stored in a SQL database, which greatly eased the filtering of the AIS data points to the area of interest and sorted the position reports by time and MMSI number. Further error correction was needed as the real-world AIS data had flaws. The two major sources of errors were identical MMSI numbers on different ships at the same time and position reports which seemed to be "stuck" in space, but not time. The first was overcome by grouping the position reports the closest last position report if there were more than one candidate for the MMSI number. For the latter, "Stuck" data points had different time of transmission, but identical position down to the last digit, and were interspersed with regular position reports. If an exact position was found to be reoccurring, all data frames with the same position were removed.

5.1 Traffic Lanes

The AIS data was split from 2375 time series delivered by the SQL server into 3232 time series. The last number includes short time series produced as a by-product of splitting the time-series. The time-series was grouped by the image matching technique described in Section 3.1 into 32 groups. Groups of incomplete time-series or stationary points were discarded after manual inspection, and the remaining groups were combined into 7 groups. Groups with 5 or less members were discarded as they represented a tiny fraction of the overall traffic situation. The end results were 5 time series groups with 2 directional subgroups each. The result of the grouping is presented in Fig.4. The number of members in each group and how the members are distributed in the directional groups is shown in Table III.

Table III: Number of Time Series in Each Group

Group	Total Members	Members in Directional Subgroups	
		"North"	"South"
1	1017	444	573
2	812	440	372
3	77	16	61
4	559	243	316
5	12	2	10

The time required for the procedure from AIS time-series to grouped results was about 30-45 minutes using a laptop with a 1.86 GHz CPU and 1GB RAM. The traffic lanes computed from the time-series groups 1 through 5 is shown in Fig.5.

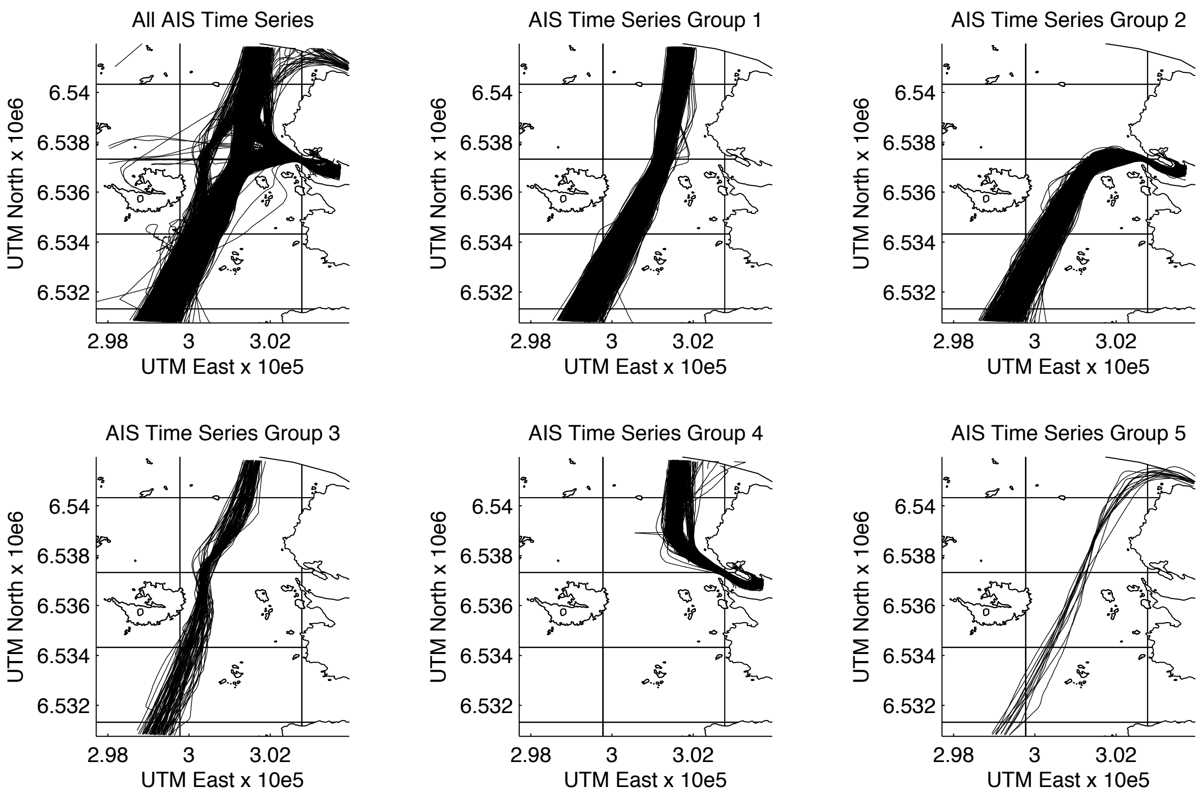

Fig.4: AIS Time Series and Results From Grouping by Comparing Track-Images

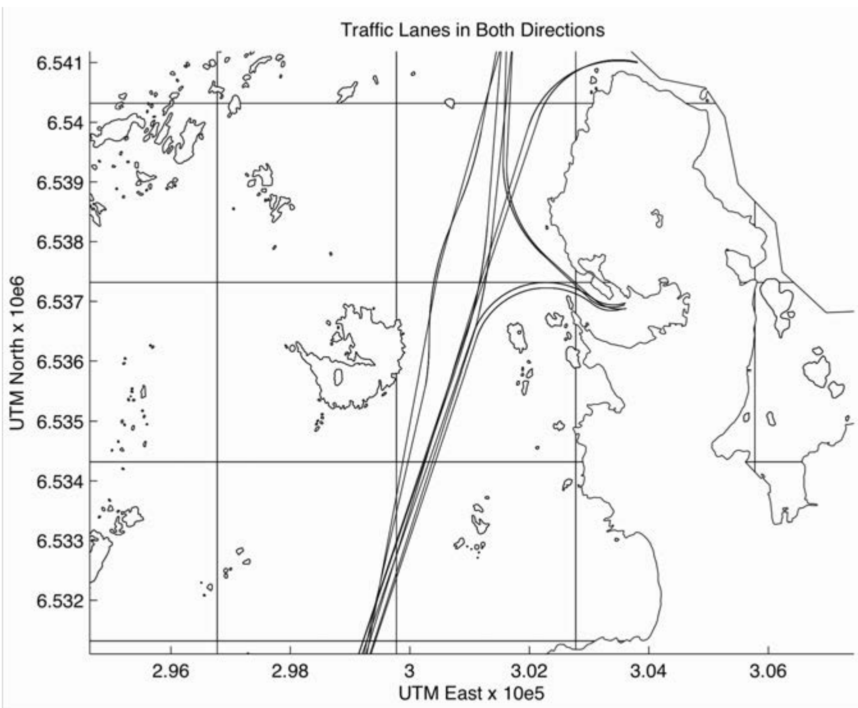

Fig.5: Traffic Lanes Computed From AIS Time Series Groups

The traffic-lanes nr 1 and 3 are similar in their points of origin and destination, but they follow a different path past the harbour area. There are navigational marking in the area between the two traffic-lanes, which results in separate traffic-lanes depending on which side of the navigation markings the ship passes. It is possible that traffic-lane 3 serve a role of conflict resolution where ships will choose it if a "head-on" encounter is anticipated if following traffic-lane 1.

Statistics from the traffic-lane "1-north" for inter-arrival time and cross-track deviation for the first section is shown in Figs.6. and 7 as histogram with fitted assumed distributions to illustrate the variation in these parameters. The real-world data follows the assumed distribution for both inter-arrival time and cross-track deviation, although the cross-track distribution exhibits a slight bias.

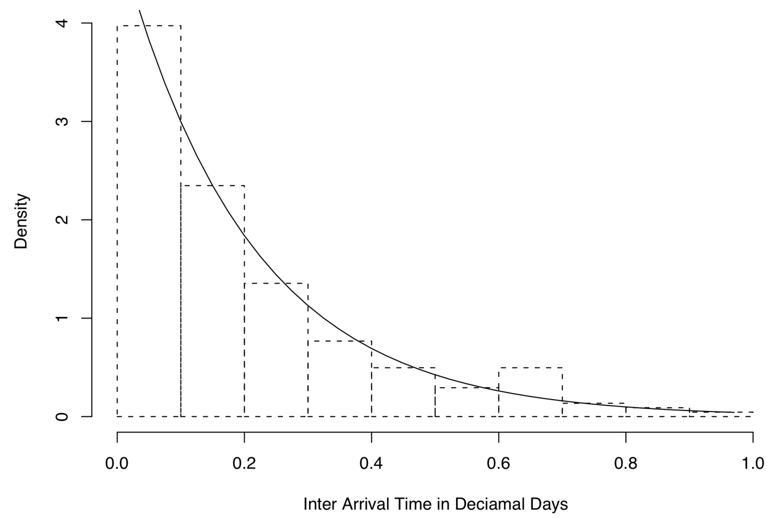

Fig.6: Inter Arrival Time for Traffic-Lane "1-North" with Exponential Distribution

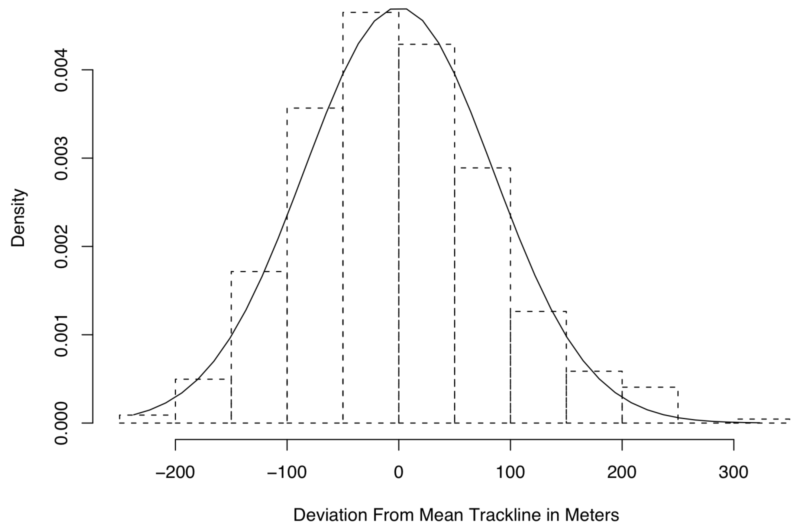

Fig.7: Cross-Track Offset at the Beginning of Traffic-Lane "1-North" with Normal Distribution

5.2 Traffic Simulations

To simulate the traffic along the traffic lanes, a simple time domain simulator was developed. The simulated model of the area had four main components.

- Model for the traffic lanes, consisting of the distribution of inter arrival times and a set of sections with associated cross-track deviation and speed statistics. Geometry and statistics was as computed for the traffic-lanes.
- Simplified model for ship dynamics with autopilot as described in Section 4
- Maneuver plan, a realisation of the traffic lane model by sampling the cross-track and speed distributions for each section at a random probability level.
- Maneuvering interaction model, an object to calculated TCPA and DCPA for two ships. Resolved "Stand on"/"Stand off" status and provided course modifications if needed.

The simulator inserted ships at the beginning of the traffic lanes at times sampled from the traffic lane inter-arrival distribution. When a ship was inserted, a maneuver plan was generated for a random probability level by the traffic lane model and assigned to the model ship. This maneuver plan contained sampled segment start and end points and sampled desired speed for each section. The realisation values were computed by selecting a random cumulative probability and making a reverse lookup into the distribution of cross-track error and ship speed for each section. The ship traversed the maneuver plan and was removed from the simulation when it had completed the last section of the plan. If two ships came closer than 2 km during the simulation an interaction object was created and shared between the ships, this interaction simulated the assessment of navigation conflict by calculation of TCPA and DCPA, comparing them to safety values and provided course offsets for conflict resolution. The resulting traffic after simulation of 24 days is shown in Fig.8. The number of independent track-lines is 677. This compares favourable with the number of track-lines in the original AIS data.

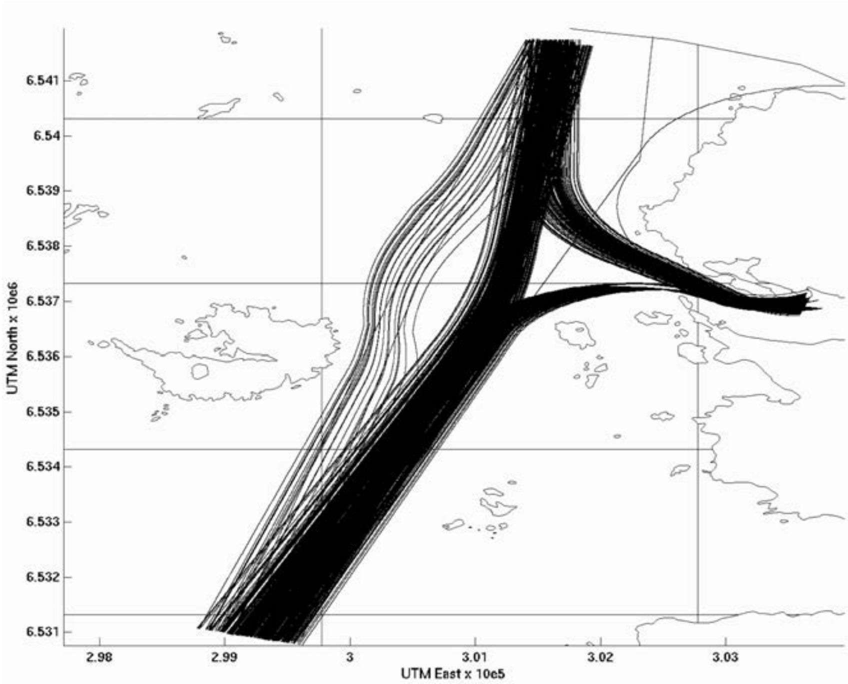

Fig.8: Simulation of Traffic along the Traffic-Lanes for 24 days

6. Discussion

The traffic situation can be adequately represented and useful information can be obtained from data available from AIS. The sample-rate of AIS, while not great, is adequate for this kind of analysis and the sheer volume of data available remedies its shortcomings. The geometric shape of the track-lines was in very good agreement with the source data, and the simulations reproduced the traffic along these traffic-lanes independent of the number of time-series used to calculate the traffic-lane shape. The variation in inter-arrival time and cross-track spread was more sensitive to the sample size. With the assumption that the cross-track spread was normally distributed, the result of fitting the distribution to a small sample size will give a result highly dependent on the properties of the samples. This became an issue with track groups "5-north" and "5-south". The error in track-spread was apparent since the track groups passed close to land having an entry/exit points close to the tip of the peninsula. The small number of ships traversing these traffic-lanes will in most cases mask the errors, but given a sufficient number of instantiations of these paths, or an unfortunate probability sample will give a maneuver plan which guides the ship to a grounding. Fig.6 shows such a case, where the track-line following traffic-lane 5 intersects with the landmass in the top right corner. The apparent intersection of traffic with the landmass at the entry of the harbor is an effect of the size each sample point is plotted with.

When the traffic enters the inner harbor, the model for the traffic-lanes breaks down since ships will berth at different positions and with different methods depending on their size and mission. The resolution of the track-images combined with the exaggeration of the pixel values, effectively destroys any information of movements in small areas. This is also the section where the calculation of the mean track-line was sensitive to track-lines continuing to berth in the narrow channel above the peninsula to the north of the harbor approach. A second simulation model for berthing/unbearthing in the inner harbor could complement the simulation of area traffic. Control of the ships could be transferred at a suitable boundary in the approach to the harbor.

7. Conclusion

This paper has shown how AIS data can be used to provide insights into the traffic patterns in an area and provide real-world maneuvering plans for usage in simulator experiments. Caution must be exercised when relying on AIS data and results must be checked to uncover unintended effects of the interaction between the assumed theoretical model and the data. AIS has shown great potential as a data collection system in addition to the role of surveillance and navigation aid it was intended for.

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Estimating Navigation Patterns from AIS

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Estimating Navigation Patterns from AIS

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The Automatic Identification System (AIS) has proven itself to be a valuable source for ship traffic information. Its introduction has reversed the previous situation with scarcity of precise data from ship traffic and has instead posed the reverse challenge of coping with an overabundance of data. The number of time-series available for ship traffic and manoeuvring analysis has increased from tens, or hundreds, to several thousands. Sifting through these data manually, either to find the salient features of traffic, or to provide statistical distributions of decision variables is an extremely time consuming procedure. In this paper we present the results of applying computer vision techniques to this problem and show how it is possible to automatically separate AIS data in order to obtain traffic statistics and prevailing features down to the scale of individual manoeuvres and how this procedure enables the production of a simplified ship traffic model.

KEY WORDS

1. AIS. 2. Manoeuvre models.

1. INTRODUCTION. Ships are the world's foremost means of transportation and are recognized as the most economical method of moving goods around the world. Due to the large quantities of cargo carried by each ship even a single accident can cause an environmental disaster and/or a serious short-term environmental impact if the cargo is discharged into the ocean. An ever increasing cargo volume carried by sea and an increased concern for the environment has led to increased focus on analysis of ship traffic both to prevent accidents and to make informed decisions about fairway design, traffic separation schemes and disposition of emergency services. This increased focus on safety has led to a need for risk analysis models for ship operations and grounding, including analysis of ship traffic and manoeuvring. Analysis of ship traffic has been hindered by a lack of data and the difficulty of obtaining data from all vessels passing through an area during a sufficient time span to produce statistics. The analysis has had to rely on limited data sets from purpose-built shore based measurement systems, data sets from selected vessel or synthetic data from simulators. Simulator studies have shown an increase in capability with the development of faster computers, but they are either limited by number if human operators are employed, or by a lack of accuracy if the human element is forgone in favour of a large number of trials with autopilot algorithms. A new possibility of data acquisition was introduced with the introduction

of AIS. Originally designed for radar augmentation and vessel traffic services (VTS), the system can be used to collect information about traffic in the area with little effort as the infrastructure is deployed around the world in compliance with the SOLAS convention. AIS provides position updates at sample rates varying from three seconds to three minutes dependent on the individual vessel's manoeuvre situation. The amount of data generated from AIS varies with the instantaneous traffic situation in the area, but if one considers historic data for traffic analysis, the amount of data to be processed increases to a hitherto unimagined scale. The amount of available information will tend to infinity if one keeps the detailed AIS records; it is evident that the previous situation of data scarcity has been replaced by an overabundance of data and that the techniques employed to analyze this data is of increasing importance if one wishes to utilize this data source to its fullest potential. Little has been published about the use of AIS for traffic analysis. Gucma & Przywarty, 2007 and Gucma & Goryczko, 2007 used AIS to provide data of the major traffic patterns and their density in the Baltic Sea to analyze the location of possible oil spills. AIS can provide data for more detailed analysis, down to the scale of individual manoeuvres, but this scale poses additional problems as the manoeuvre patterns in AIS position reports fall into groups defined by geometry not by some measure of absolute position. This problem is further enhanced by analysis of areas where no prior knowledge of manoeuvre patterns exist, making the problem both the identification of manoeuvre patterns and the grouping of the data according to these patterns.

This paper will show how one can utilize AIS as a data source to explore the existing manoeuvre pattern in an area, estimate the manoeuvre sequence and generate traffic statistics by application of computer vision theories. The process produces an idealized description of the manoeuvring pattern and statistics with relatively little effort. In addition it will be shown how to utilize databases of publicly maintained navigational aid installations to estimate the most probable navigational aid used for transitions in the manoeuvre sequence.

2. METHODOLOGY.

The selected area of study shown is in Figure 1. Position reports were obtained from AIS data collected in the period of April to June 2006. The area is that surrounding Risavika harbour in south-western Norway and shows a clear traffic pattern. The premises of application of computer vision techniques to explore and group the traffic in an area are:

- There are well defined manoeuvre patterns which can be detected by looking at the traces of the ship positions.
- A prototypical manoeuvre plan is, or appears from external observations, shared by vessels following a manoeuvre pattern.

The assumptions are fulfilled in constrained waters where geographical features restrict traffic and either prescribe a particular manoeuvre plan, or necessitate an orderly manoeuvre execution. A typical collection of position reports in constrained waters from AIS is seen in Figure 1, which exhibits several overlapping, and well defined traffic patterns.

2.1. *AIS as a data source.*

AIS was introduced in a SOLAS amendment and is a recent addition to the required bridge equipment aboard vessels in domestic and

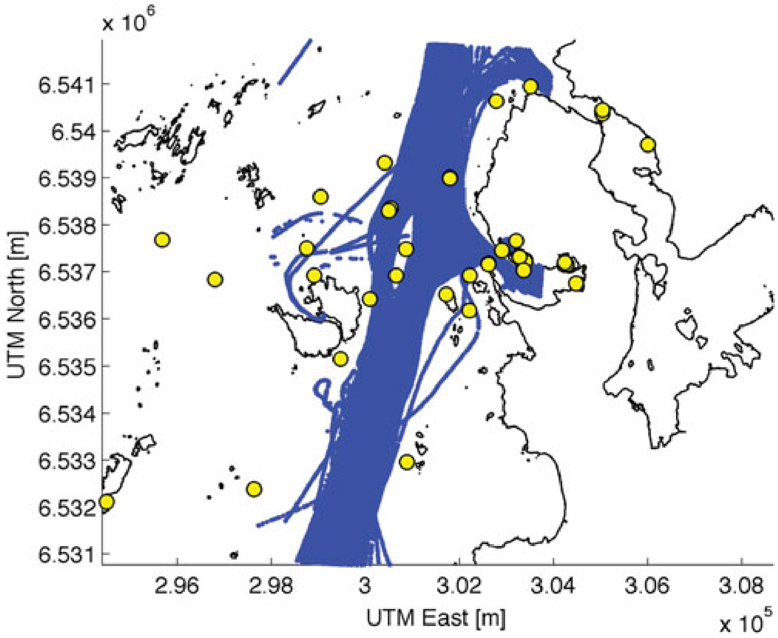


Figure 1. AIS samples in blue and navigational markings in yellow in an area where traffic is constrained by land and island formations.

international traffic. The system connects the ship's global positioning and speed measurement systems to a transponder, which broadcasts the ship data. The AIS data is received by other ships as well as base stations along the coast, and is used both by ship-based ECDIS and VTS control centres for surveillance and radar augmentation. The system is self-organizing by a time division multiplexing algorithm and provides updates to variable data at rates depending on the ship's speed and manoeuvre situation. The data broadcasted from an AIS transponder is divided into static, semi-static and dynamic data.

- Static data: Ship identification number (MMSI number), length and breadth.
- Semi-static data: Ship destination, hazard level of cargo and ship draft.
- Dynamic data: Time of broadcast, ship speed, rate of turn, course over ground and position.

The rate of data transmission is seen in Table 1. The data rates are sufficient to conduct manoeuvring pattern studies, and the time-code multiplexing algorithm of the system provides space for about 1000 vessels at the same time; a limit which the amount of traffic in the studies area is well below. The accuracy of the position data transmitted is limited by the accuracy of the ship-borne global positioning system. While there are different satellite positioning systems available or in development GPS is the leading system currently deployed. While the accuracy of GPS originally left something to be desired, the development of differential GPS systems and advances in positioning algorithms has greatly increased the accuracy of the position measurements from GPS. The currently installed set of global positioning systems in the world fleet is a mix of low and high quality receivers. This mix of position quality directly influences position reports in AIS and can be exaggerated by the use of low quality receivers on recreational vessels or on vessels where AIS is perceived as being unnecessary equipment. This heterogeneous data quality can be

Table 1. Sample rate of variable data from AIS.

Manoeuvring Situation	Sample Rate
At Anchor	3 min
Speed 0–14 knots	12 s
Speed 0–14 knots and changing course	4 s
Speed 14–23 knots	6 s
Speed 14–23 knots and changing course	2 s
Speed >23 knots	3 s
Speed >23 knots and changing course	2 s

perceived as noise in the position data and be countered by relying only on repeated similar series of position reports and using the median values to arrive at a description of the traffic.

AIS data from the greater area around Stavanger in the south-west of Norway was delivered by the Norwegian Coastal Administration. The data contained MMSI number, time of transmission and dynamic AIS data. The AIS reports are not in the form of ship position reports in a sequence, but as a stream of packets from different ships as received. To apply the data from AIS in manoeuvring analysis, the data for individual ships must first be reconstructed. This reconstruction is achieved by use of the unique MMSI number and the time of broadcast with which every data frame is marked and allows the sorting of data from AIS into time series for each different MMSI number. There are various error sources in AIS data as reported in (Harati-Mokhtari et al., 2007) and (Norris, 2007), ranging from data corruption, erroneous MMSI number, target swaps, faulty position reports and errors in rate-of-turn data. Faulty position reports as encountered when there is a problem with the receiver (Norris, 2007; Graveson, 2004) are handled in historic analysis by the selection of samples by area. Erroneous MMSI numbers are difficult to compensate for if there is more than one transponder in the area broadcasting the same number; target swaps and duplicate MMSI numbers were filtered out using a filter based on comparing distance between samples and the possible distance covered at the reported speed and time difference. To account for situations where a ship might leave the studied area and reappear, the resulting time series from the MMSI groups were split at major discontinuities in time. Detection of these discontinuities is achieved by the mean and standard deviation of the sample rate for each specific MMSI number. The presence of harbours in the area is accounted for by removing sections in the time series where the ship has zero speed. It was found that in the absence of velocity data the field reserved for speed in the navigation message is set to 127 (all 8 bits set), thus the operation had no effect on time series where speed data was missing.

2.2. *Model for ship traffic in restricted waters.* The analysis of traffic in an area must be supported by an underlying theoretical model for the traffic and it must capture the features of the underlying process. In the case of ship traffic, the underlying process is ship manoeuvring and the representation of the data is conceptually divided into three levels:

- Time-series: A collection of sequential data of a single ship's manoeuvre process.
- Traffic-Group: Collection of the time-series of ship traffic following a similar geometrical pattern in the same direction of travel.
- Area-traffic: The result of the combination of all the traffic-lanes in the area.

The aggregation of similar geometric patterns is based on the assumption that a similar manoeuvre process will produce a similar geometric trace of ship movements. The traffic-group is positioned as the aggregation of the individual ship movements into the traffic patterns we observe in retrospect. The traffic-group enables the median path and spread of traffic to be measured and can provide useful statistics about the current traffic situation. Median values and statistics cannot alone model the traffic pattern and only help to summarize the traffic situation. To find a meaningful model we turn to the process behind the results, that of ship manoeuvring, to provide a suitable description of the manoeuvre process of the traffic-group.

2.2.1. *Manoeuvre model.* The process of ship manoeuvring is assumed to follow a pattern where specific manoeuvre strategies are executed in sequence to produce the desired outcome. The traffic-group can then be represented by the execution of one specific manoeuvre strategy in a part, or section, of the traffic-group. The admissible manoeuvres in a traffic-group are limited and are represented by a necessary simplification since it is impossible to discern between manoeuvre types other than course changing and course keeping by analyzing position and speed reports. This results in a model of manoeuvring where a course keeping strategy is selected for sections without course change. For sections with course change a strategy where control of the relationship between the rate of turn and speed is executed to place the vessel on a circular path is selected. The strategy of turning the ship along a circle gives the master a procedure to control the future position of the vessel in restricted waters while executing a course change. This idealized representation is inspired by (Lützhöft & Nyce, 2006) and (Aarsæther & Moan, 2007) where the approach is observed both in planning manoeuvres and in training programmes. While different manoeuvre strategies can be expected to be employed, the simple line-circle representation is intended as a low-resolution representation of the manoeuvring process. The numerical parameters required for the manoeuvre model are derived by the information needed to specify each manoeuvre. The following properties are used to initiate a specific manoeuvre from the idealized representation:

- Straight line: Course angle of the line and speed
- Circle section: Radius of turning circle, course change and speed

The total traffic model for an area is obtained by superimposing the different manoeuvring patterns. This neglects the interaction of ships following different manoeuvre patterns, but the simplification is a necessity as it allows the treatment of different manoeuvre patterns separately. The manoeuvre parameters of each section in the traffic-group are specified as statistical distributions to capture the variation of the ship traffic. The final model is the idealized description as a collection of straight line segments connected by tangential circles with probability distributions for the parameters of each segment. The model for ship manoeuvring can then be illustrated by Figure 2, which shows an ideal path of the traffic-group with manoeuvre sections along with a typical observed case. The defining geometric characteristics of each manoeuvre are indicated with Ψ being the actual course and R the radius of turn manoeuvre. δ is the possible perpendicular offset from ideal path, or spread of the traffic.

2.2.2. *Manoeuvre transitions.* The transition between different manoeuvre strategies is triggered either by an external condition such as the vessel's orientation

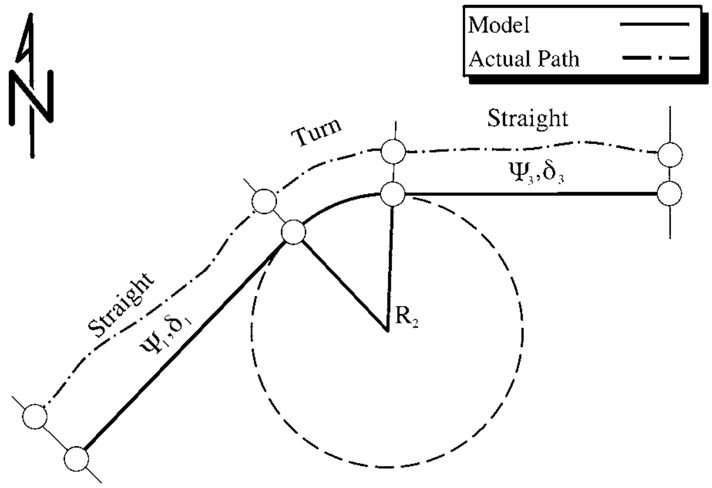
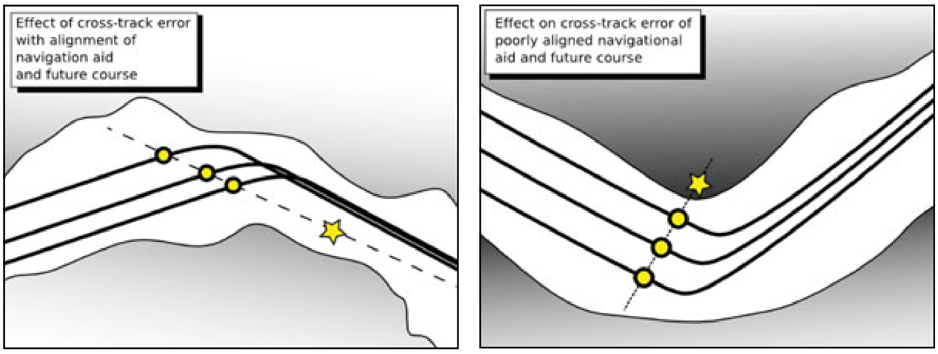


Figure 2. Manoeuvre pattern model.



(a) Parallel to next course

(b) Perpendicular to initial course

Figure 3. Effect of navigational aid selection on the evolution of cross-track error along the path.

relative to landmarks and navigational aids in the fairway, or by the evolution of vessel specific variables like course and position. The location of all the navigational aids in Norwegian waters is recorded by the Hydrographic Service of The Norwegian Mapping Authority. The records of the navigational aids are available in machine readable form with coordinates, name and type available for each installation. This data source is cross-referenced with the results of inferring the manoeuvre plan to produce the probable conditions used to transition between manoeuvres. The choice of transition condition is critical since it greatly influences the end result of the method. The applied condition is based on the aptitude of the navigational aid to provide consistent identification of a beneficial transition point in order to minimize the propagation of cross-track error along the path. This is achieved where the object selected for reference is an apparent bearing as close as possible as the next course. An illustration of the result achieved with this selection of navigational aid is seen in Figure 3a where course lines with identical shape and initiation of turn are superimposed with different cross-track errors. It is worth noting the difference with a selection of a bearing to navigational marking that is indifferent to cross track error as in Figure 3b. The propagation of the cross-track error is minimized with a decreasing difference between the bearing to the selected navigational aid and the next desired course angle at the desired transition point. This principle of navigation is

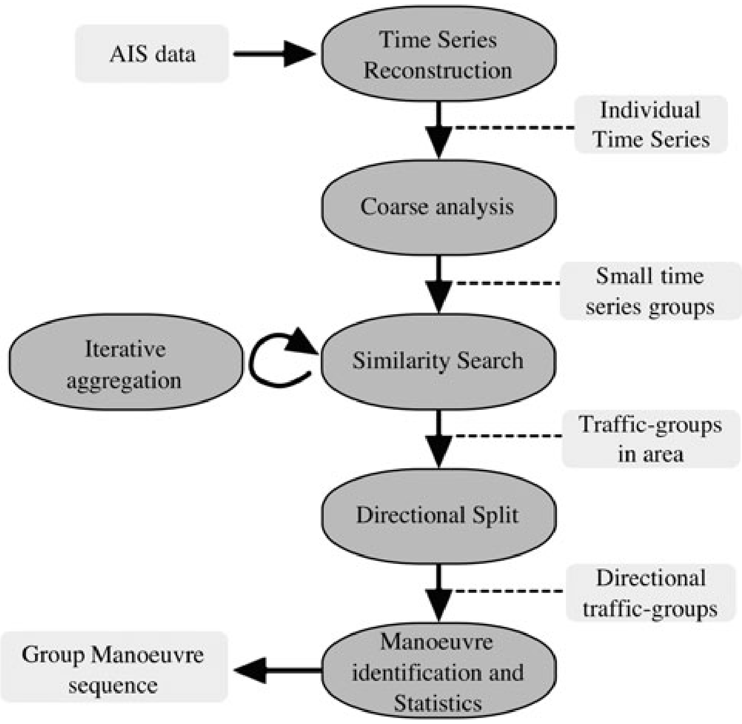


Figure 4. Flowchart of the process to transform AIS samples to a sequence of manoeuvres.

selected as the guiding mechanism to identify the condition and navigational aid used for transitions between straight and turn segments.

2.3. *AIS data frames to manoeuvre model.* The process of converting AIS data of the ship traffic in an area into an idealized description separated into individual manoeuvres is a multistage process. It starts with the time-series reconstruction and proceeds with the aggregation of the individual time-series into traffic-groups which are further analyzed to yield traffic statistics and a sequence of manoeuvres followed in both directions of the traffic-groups. A conceptual flowchart of the process is seen in Figure 4.

2.3.1. *Track-line registration.* The problem of automatically detecting and comparing and tracking features in images has been explored in the fields of computer vision and medical imaging. The task of comparing images to produce an objective measure of their similarity is named image registration, a technique which is used to stitch satellite images for GIS and in medical imaging. Image registration techniques are surveyed in (Zitova & Flusser, 2003) and (Brown, 1992) and can be divided into two major categories:

- Feature based, comparison of aggregated features of identified shapes in an image-like area centre and intersections.
- Region based, test of similarity in image intensities.

These methods can be used to detect the overlapping regions of images or to find areas in images that match a reference shape. These techniques can be applied to the problem of manoeuvring analysis to separate traffic into groups of similar geometric shapes. In order to apply these methods, the AIS data had to be presented as digital images such as monochrome images that are represented as a matrix of grey-scale intensities in the range [0, 1]. To transfer the AIS position reports to an image representation, the area was discretisized by a partition into 75-by-75 metre bins with the number of position reports in each bin as the grey-scale values. The resulting resolution of the area becomes 83×150 pixels with this bin size. The density of position reports from AIS shows the intensity of ship traffic in the area, but individual reconstructed time-series treated in the same way result in an image of representation of the position trace for a particular ship.

The application of image registration techniques is well suited to organize the track-lines into geometrical similar groups and the artificial image representation of the AIS samples is well suited for such an application since it is generated in controlled circumstances. The controlled transfer of remotely sensed data into a discrete representation of the position traces simplifies registration by removing the need to consider differences in resolution and geometrical distortions expected in images collected from optical equipment. While the image resolution and geometric distortions are eliminated, the offset in North (x) and East (y) direction of individual position traces following the same manoeuvre pattern is not. To compensate for the slightly different imprint of each time-series, the image representation is augmented by extending each sample by three pixels in each direction. To reduce processing time the sorting of position traces was divided into a coarse and detailed analysis. The coarse analysis simply looked at the correspondence of track images without accounting for possible translations. If two images were deemed similar, future comparison was done with the mean track of the two. The coarse analysis left a large number of small groups, which were used as inputs to the detailed analysis. To compensate for possible translations in x and y direction the similarity between the track-line images was measured by computing the cross-correlation between two images for translations in North and East direction. The magnitude of the admissible variation in translation must be carefully selected based on the traffic in the area, the displacement must be allowed to cover as much of the traffic as possible, but it must also be restricted so as to counter mis-registrations of similarly shaped traffic groups in different parts of the area. The track-group image is used as a template image which the procedure attempts to find in the track-line image which is tested. To implement the search for maximum similarity by translation the template image is extended 10% in each direction, and the (x, y) translations (u, v) allowed to vary between 0 and 20% of the image size in each direction. The cross correlation function will have a maximum for a specific translation (u, v), and the relative degree of similarity between the images is obtained by dividing the resulting maximum in the cross-correlation function with the total image intensity of the original image. The equation for the cross-correlation between the track-line group image and the track-line template for a translation (u, v) is seen in Equation 1 which is a slightly modified version of the formula presented in (Brown, 1992), where T is the template image, I is the image we wish to test and the pairs (x, y) & (u, v) denotes pixel position in the images and translation offset for the test image. The normalization factor is modified to account for the presence of only 0 and 1 in the image which simplifies the sum of absolute image intensities to the number of nonzero pixels; this eliminates a computationally expensive matrix multiplication and square root computation.

$$CCR = \frac{\sum_x \sum_y T(x,y) I(x-u, y-v)}{\max\left(\sum_x \sum_y I(x-u, y-v), \sum_x \sum_y T(x,y)\right)} \tag{1}$$

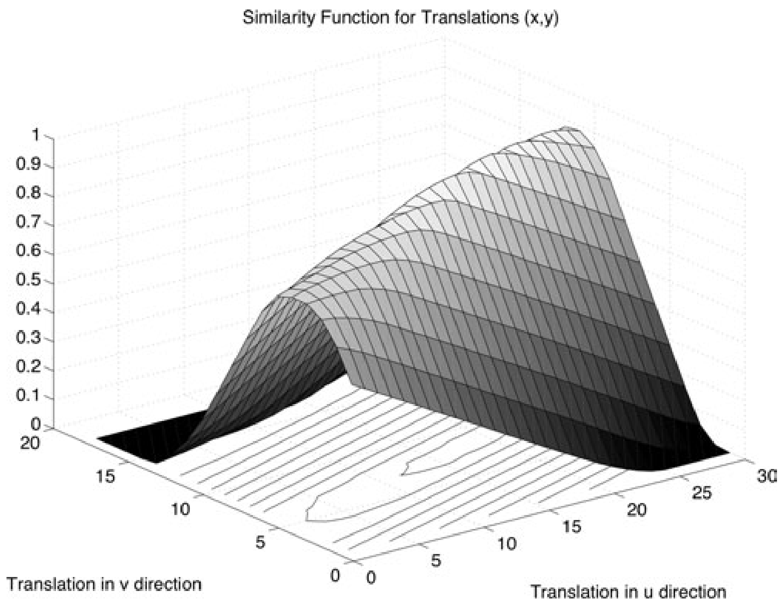


Figure 5. Surface of image similarity function for translations in x and y direction.

Equation 1 measures the percentage of overlap between the pixels between the reference image and the tested image with a translation (u, v) and produces values in the interval [0, 1] for each possible (u, v) pair. The Equation 1 maximum is desired as it indicates the maximum degree of similarity obtainable between the two images. The maximum of Equation 1 is found by formulating the image similarity as a constrained non-linear optimization problem with constraints placed on the maximum translation between the two images. Discrete optimization techniques, such as branch-and-bound, are not applied due to the computational complexity. The function value at an arbitrary decimal (u, v) translation is found by interpolation in two dimensions inside the set of points enclosing the translated (x, y) pair. The precise location of the maximum is not relevant in this analysis and the interpolation strategy provides the benefits of sub-pixel accuracy in the search for a maximum. A detailed derivation of optimization and interpolation strategies is found in (Nocedal & Wright, 1999; Press et al., 2007). The selected method is a simple gradient descent search where the gradient is estimated from object function values. The standard optimization method employed only guarantees the convergence to a local, not the global, maximum. The function is expected to have several local maxima due to variations in the real-world data. The robustness of the solution is therefore verified by performing searches for the maximum starting at a set of initial translation values. A typical plot of the similarity function in 2D for two similar track-line images is seen in Figure 5. The detailed analysis combined the groups from the coarse analysis by an iterative process where groups that showed a maximum correlation were combined. The final operation was to divide the geometric groups into two subgroups depending on the direction of travel.

2.3.2. *Track-line group analysis.* With the time-series sorted into groups of similar shape, the groups were divided into two subgroups depending on the direction of travel. These directional groups form the basis of traffic-group analysis. The desired output value from the analysis is the idealized representation of the time-series group as a set of interconnected straight lines and turn manoeuvres with associated statistics. The time-series reconstructed from AIS have heterogeneous sample rates,

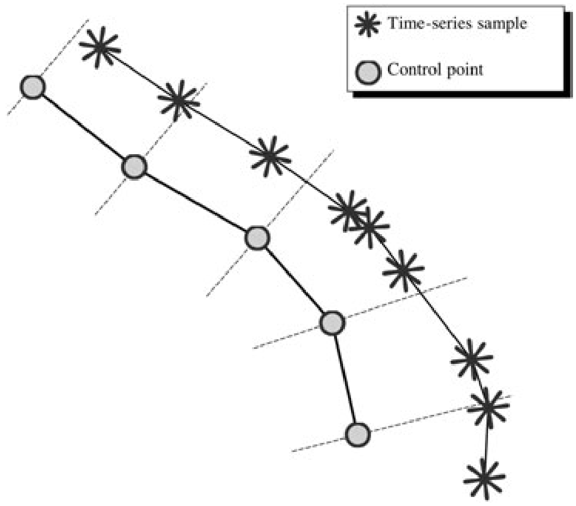


Figure 6. Index mapping between evenly spaced control points and the variable spaced time-series points. Perpendicular lines at the control points show the intersections where speed and cross-track offset are calculated.

within the geometric similar group, and even within the individual time-series. This necessitates a transfer of individual time series data to a common representation, which compensates for the variations in sample-rates. Control points were computed as the mean points of 100 evenly spaced points for each time-series belonging to the group. The control points were computed as the median value of points at 1% increments of the total time-series' geometric length. To establish a mapping between the time-series samples and the control points of the traffic-group the intersection between the position traces and a perpendicular line of each control point was found to establish index map of the time-series' onto the traffic-group. An illustration of the mapping procedure is seen in Figure 6 where the inhomogeneous sample rate of the time-series is related to the evenly spaced control-points. Vessel speeds at the control points were found by mapping the control point indices onto the time-series and values for cross-track spread as the distance from the median point to the intersection along the perpendicular vector. This provides the statistical summary of the traffic along the traffic-groups length. Separation of the traffic group into a sequence of the two manoeuvre types is achieved by analysis of the median curvature κ of the time-series' at the control points.

2.3.3. *Curvature calculation.* The curvature κ of the ship's track can be calculated from the position and time data. This can be done by filtering the position data to remove noise and then using a numerical expression for the curvature calculated by solving the equation for a circle passing through the three consecutive points. κ can also be obtained directly from the time domain signals for the position $x = x(t)$ and $y = y(t)$. The curvature of these two signals in Cartesian coordinates with Φ as the tangential angle of the signal is:

$$\kappa = \frac{d\Phi}{ds} = \frac{d\Phi/dt}{ds/dt} \tag{2}$$

$$\kappa = \frac{d\Phi/dt}{\sqrt{(dx/dt)^2 + (dy/dt)^2}} = \frac{d\Phi/dt}{\sqrt{\dot{x}^2 + \dot{y}^2}} \tag{3}$$

The need for dΦ/dt can be eliminated by the following identity:

$$\tan\Phi = \frac{dy}{dx} = \frac{dy/dt}{dx/dt} \tag{4}$$

$$\frac{d\Phi}{dt} = \frac{1}{1+\tan\Phi}\frac{\dot{x}\ddot{y}-\dot{y}\ddot{x}}{\dot{x}^2} \tag{5}$$

Equation 5 substituted into 3 gives the final expression for the curvature calculated from the x and y time domain signals:

$$\kappa = \frac{\dot{x}\ddot{y}-\dot{y}\ddot{x}}{(\dot{x}^2+\dot{y}^2)^{3/2}} \tag{6}$$

This expression for κ relies on the derivative and double derivative of the vessel track line positions. Numerical calculation of these derivatives from noisy position data is inherently error prone. Instead of calculating the derivatives numerically, the derivatives are evaluated by fitting polynomials to the x(t) and y(t) signals. It is impossible to find a general polynomial to describe the complete track with sufficient accuracy for the entire ship track. To calculate the curvature at a specific track sample, a 5th order polynomial is fitted to a section spanning 20 samples both forward and backward in time. This provides both a theoretical form for the evaluation of the derivatives and suppresses the noise in the positioning data. The derivatives and double derivatives can then easily be evaluated from the corresponding formulas for polynomials. The polynomial fit was computed using MATLAB's POLYFIT function using both centring and scaling to improve the numerical properties of the fitting procedure.

2.4. *Identification of manoeuvres and navigation aids.* The separation of the traffic-group into straight and turn sections is based on the features of the groups' curvature trajectory. The group curvature was found by applying the mapping between the individual time series and the control points of the traffic-group. The median value for curvature at each control point was selected to form the curvature of the entire group at the control points. The identification of turn and straight sections was based on an ad-hoc method applying the mean (μ) and standard deviation (σ) of the median curvature trajectory. If a point on the trajectory was outside a low curvature band defined by $\mu \pm 2\sigma$ the point was identified as being in a turn-manoeuvre. This procedure was repeated twice by recalculating the mean and standard deviation of the identified straight section of the curvature trajectory and assigning any outliers to the turn segments.

The prescribed geometric model with straight lines interconnected by turns reduces the task of segment separation of the individual time-series to the identification of the turn segments, any part of the time-series not belonging to a turn section must by definition belong to a straight section. The manoeuvre pattern of the group is replicated with some variations in each time-series. In order to measure the variation of the manoeuvre parameters of the entire group, the manoeuvres in the time-series must correspond to the individual manoeuvres in the group. This mapping is especially important when identifying the most probable navigational aid, since each time series will have slightly different transition points between manoeuvres. The situation of the slight variation in the location of the individual manoeuvres in time

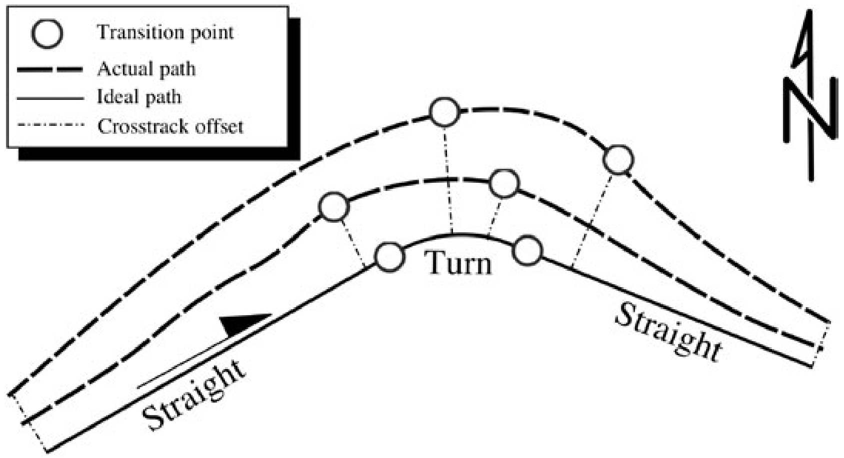


Figure 7. Separation of time-series into manoeuvre sequences. The manoeuvre sequence in the ideal path is shared but the precise location of the transition points between manoeuvres varies.

and space is seen in Figure 7 where the differing manoeuvre transition points in relation to the median track of the directional group are shown.

Image registration techniques were applied to identify the turn sections from the curvature of the directional traffic groups in the curvature of the individual time-series. This was achieved by creating an image representation of the curvature of the directional group turns and maximizing similarity between each of the group turns and the curvature trajectory of the individual time-series. This process is illustrated in Figure 8 where the turns of the traffic-group are separated and transferred to image representations and the maximum correlation between these images and the time-series curvature is used to identify the execution of the group pattern in an individual case. Equation 1 was again applied, but the denominator was simplified to only scale for overlap of the pixels in the isolated turn images. Ordering of the turn sequence was enforced by limiting the image similarity search to the part of the trajectory following the last identified turn section. The location of the individual time-series turns was the midpoint of the turn structure identified with turn border points modified by shifting them with the offset of the maximum correlation. Most probable navigational aid for the initiation of turns was identified by considering the bearing from the vessel to all the navigational aids in the area at the turn initiation point located by the image registration based procedure. The criterion used was to find the minimum difference between the apparent angle to the navigational aid and the next desired course angle. The name and index of the identified navigational aid for each time-series was stored for later analysis.

3. RESULTS.

The AIS data was stored in an SQL database and indexed after MMSI number and time, this made the process of obtaining AIS position reports ordered by time for a particular vessel straightforward manner with standard SQL queries. The time series was separated as described above resulting in excess of 3600 cases, time series shorter than 15 samples were then excluded resulting in 2763 cases with a total of 513,533 position reports. The exclusion criterion was based on the distribution of sample lengths. Some time series were short because they were by-products of the time-series splitting procedure. This can result from periodically

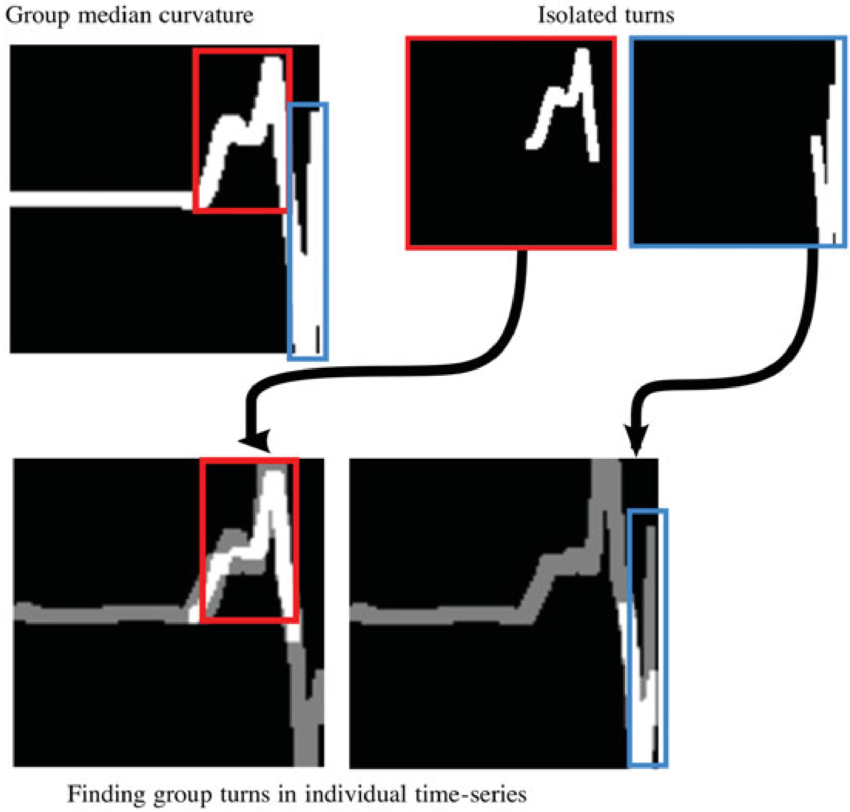


Figure 8. Finding the group manoeuvre sequence in an individual time series. The curvature of the turns in the traffic-group is isolated and the most probable location of the group turns is found in an individual time-series by maximizing the similarity between the isolated group turns and the curvature of the time-series. The overlap between the median curvature and the individual time-series curvature is seen as white, and non-overlapping regions as dark grey.

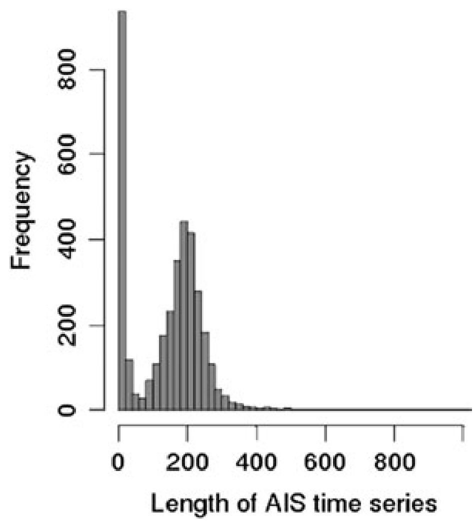


Figure 9. AIS time series length showing a large component of very short time series from reconstruction.

exceeding the speed threshold used to split time-series to remove stationary vessel data, and the time series were removed to reduce processing time. The distribution of time series lengths is seen in Figure 9. It is evident that there is a component of

Table 2. Distribution of time series in traffic groups.

Traffic group No.	Total	Direction North	Direction South
1	1016	443	573
2	809	436	373
3	76	16	60
4	551	240	311
6	17	4	13
7	11	2	9
SUM	2482		

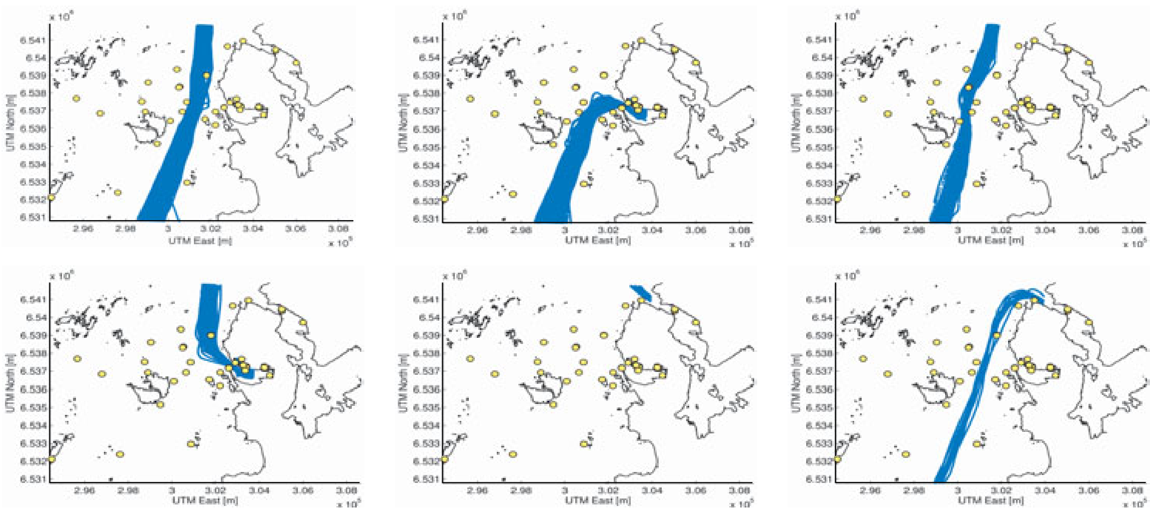


Figure 10. Separation of traffic by geometry into groups, which shows the overlapping traffic patterns present in the area.

very short time series containing a small fraction of the total number of samples. The remaining time series were used as input for the traffic-lane construction. Image registration was implemented in MATLAB with FMINCON from the optimization toolbox used for maximization of image similarity.

3.1. *Traffic separation and statistics*. The number of time series in each group is shown in Table 2 which also includes the breakdown of traffic in the two travel directions. The traffic-groups are numbered and shown in sequence in Figure 10; the median track of the resulting directional traffic-groups is shown in Figure 11.

Traffic group No. 5 is not included since it refers to vessels at anchor in the harbour. The number of time series in each group reveals that most of the traffic in the area follows the main traffic-lane crossing the area in the North/South direction. The other main traffic-lanes are those entering and leaving the harbour in the area. Three other auxiliary traffic-lanes are also visible with group No. 3 representing traffic crossing westward of the navigation markings in the approach to the harbour, group No. 6 a small part of another traffic-lane intersecting with the north-east corner of the area and group No. 7 showing a small component of traffic between the north-east corner and the mid-point of the southern border of the area. It is worth noting the difference in traffic density between the three densest and the following sparsely

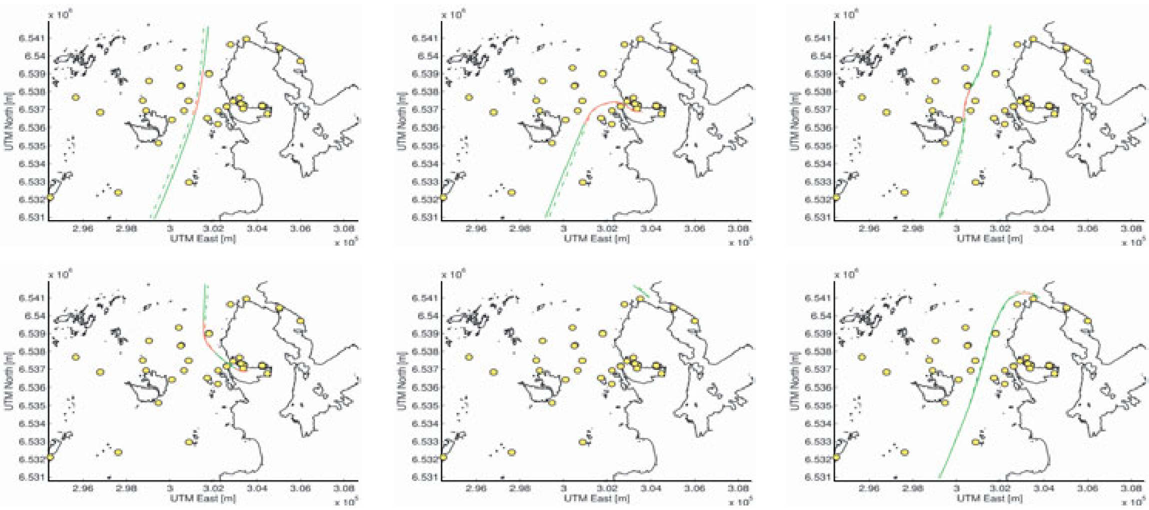


Figure 11. Median track of the traffic-groups in Figure 10. Median track is shown for the directional groups ''North'' (continuous line) and ''South'' (dash-dotted line), with high curvature sections shown in red.

populated traffic-groups. The low number of passages in the three least populated traffic-groups implies a limited accuracy of any statistical description of the traffic. While the quality of the quantitative measures for those lanes are lacking, the information they provide regarding rarely occurring manoeuvre patterns can provide interesting scenarios of interfering traffic for risk-analysis and crew training pertaining to this particular area. Relevant statistics were collected for each section.

- Straight section: Median speed over section, cross-track deviation from median value at start and end and average course angle over section.
- Turn section: Median and mean curvature over section, median speed and course angle at exit.

The variables for each section were fitted to the skew-normal distribution (Azzalini 1985). The skew-normal probability distribution was chosen since it defines a class of distributions which contains the regular normal distribution, but in addition allows the data to exhibit a bias capturing the deviations from the normal distribution one would expect from measurements. The skew-normal distribution is an extension of the normal distribution and still retains the association with the central limit theorem due to its close link with the normal distribution. While the normal distribution is a two-parameter model fully specified by the mean and standard deviation, the skew-normal distribution is a three-parameter model with location, scale and shape required to fully specify the model. The location and scale of the skew-normal distribution are analogous to the mean and standard deviation of the normal distribution while the shape parameter is introduced to represent the bias of the underlying process, with a shape variable of 0 the normal distribution is recovered. The skew-normal distribution was preferred due to its simplicity and yet the ability to capture the wider range of behaviours encountered in ship traffic and manoeuvring analysis.

3.2. *Manoeuvre plan inference.* The inference of the applied manoeuvre plans in the area is a two-step process, the first task is to identify the sequences of straight and turn manoeuvres in the time-series groups. With the manoeuvre type and sequence in

Table 3. Manoeuvre sequence and statistics for sample group "North 2".

Section	Variable	Location	Scale	Shape
1 Straight	course (rad)	0·298	0·042	0·713
	offset start (m)	−133·18	239·12	0·991
	offset end (m)	−86·95	130·60	1·137
	speed (knots)	10·44	3·26	1·277
2 Turn	median κ (m^{-1})	−8·45e−4	3·0e−4	−1·934
	extreme κ (m^{-1})	−1·3e−3	1·21e−3	−6·221
	speed (knots)	7·65	3·75	1·795
3 Straight	course (rad)	2·373	0·15	−2·277
	offset start (m)	17·43	39·76	−1·53
	offset end (m)	12·18	30·68	−0·771
	speed (knots)	6·28	3·23	2·135
4 Turn	median κ (m^{-1})	8·956e−4	1·24e−3	1·452
	extreme κ (m^{-1})	3·77e−4	2·81e−2	1·534e3
	speed (knots)	4·64	2·65	1·184

each group established, statistics for the manoeuvre parameters of each section are derived from the parameter values from the corresponding time-series sections using the manoeuvre to time-series map. The completion of the manoeuvre plan comes from the identification of the most probable navigational aids and the corresponding bearings from vessel to navigational aid for each transition from a straight section into a turn. A full treatment of the manoeuvre plan for all the traffic groups with two direction is not possible due to lack of space, so the directional groups "North 2" entering the harbour starting at the southern border and "North 4" leaving at the northern border starting in the harbour are selected to illustrate the procedure. These directional traffic-groups were selected since they represent the manoeuvre sequence of the most complicated traffic patterns in the area. It was assumed that the effect of travel direction within each group was negligible, and the selection also shows the two situations of traffic entering and leaving the harbour.

3.2.1. *Manoeuvre sequence.* Manoeuvre sequences and estimated parameters for skew-normal probability distributions are shown in Tables 3 and 4. The sequence of manoeuvres and their statistical properties are seen to be very consistent with the properties of the corresponding sample-groups shown in Figures 10 and 11. It is worth noting the correspondence of the statistics for the two straight sections, which enters ("North 2" section 3) and leaves ("North 4" section 2) the harbour in the two manoeuvred sequences. It should be noted that the underlying assumptions about the traffic patterns breaks down in the harbour area, and the results dependent on course and curvature suffers from the relative divergence in course as the vessels manoeuvre for berthing in different parts of the harbour. The discretization of the area has insufficient resolution to capture this effect, and it is not desirable to separate the traffic flows in and out of the harbour from their future or past berthing point. This leads to a high degree of uncertainty about the curvature and final course angle of section 4 in "North 2" and section 1 in "North 4". The statistic for speed is unaffected by this issue since it will reflect the median speed while manoeuvring in the harbour.

3.2.2. *Manoeuvre transition.* The transition points in each time series were identified by applying the mapping from identified sample-group turns to the individual

Table 4. Manoeuvre sequence and statistics for group "North 4".

Section	Variable	Location	Scale	Shape
1 Turn	median κ (m^{-1})	−8·72e−4	1·56e−3	−1·973
	extreme κ (m^{-1})	−8·32e−4	2·20e−2	−1·534e+3
	speed (knots)	4·67	3·53	2·461
2 Straight	course (rad)	−0·860	0·11	2·203
	offset start (m)	23·82	40·17	−1·323
	offset end (m)	34·62	113·26	−1·104
	speed (knots)	8·02	4·06	2·941
3 Turn	median κ (m^{-1})	−5·08e−4	4·58e−4	−2·661
	extreme κ (m^{-1})	−4·88e−4	7·30e−4	−9·343
	speed (knots)	8·28	4·191	3·268
4 Straight	course (rad)	0·01	0·06	1·673
	offset start (m)	−108·62	152·77	1·374
	offset end (m)	−118·57	163·16	2·34
	speed (knots)	8·56	4·31	3·437

Table 5. Relative frequency of most probable navigational marking.

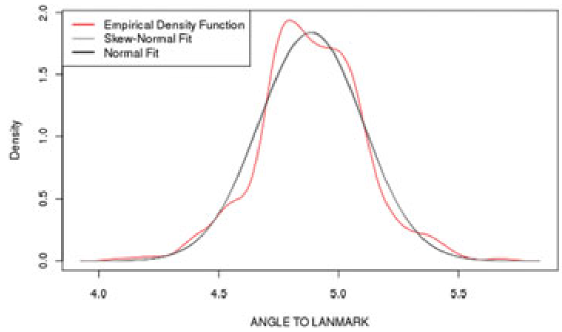
	Navigational marking	
Traffic group, section	Name	Frequency
"North 2", section 2	Flatholmen	1·0
"North 4", section 3	Nesjaflu Lysbøye	0·6835
	Nesjaflu	0·2447
	Hillebåen	0·0717

time-series. The transition points into and out of the turn manoeuvres were identified for all time-series and the median of the course angle at the end of the turn manoeuvre was used to represent the future desired course at the start. The difference between the current course and the estimated future desired course provided an estimate of the ideal bearing to a navigational marker used to initiate the turn for each time series. The apparent angle from the vessel to all the navigational markings in the area within one nautical mile was calculated at the turn initiation point and compared with the course difference between the current and future desired course. The navigational mark with the minimum discrepancy in the course difference was selected as the most probable navigational marking. The relative frequency of most probable navigational marking is seen in Table 5. For "North 2", section 2, there is only one probable navigational marking, while "North 4", section 3, is dominated by two markings sharing the same location. The angle from the vessel to the navigational aid for the dominating installations in the identification in each turn initiation is seen in Figure 12a and Figure 12b–12c for section 2 of "North 2" and section 3 of "North 4" respectively. Statistical parameters for the distributions of angle to navigational aid are seen in Table 6. Angles are calculated as negative to starboard of the vessels, objects with apparent angles greater than π are to the starboard side of the vessel.

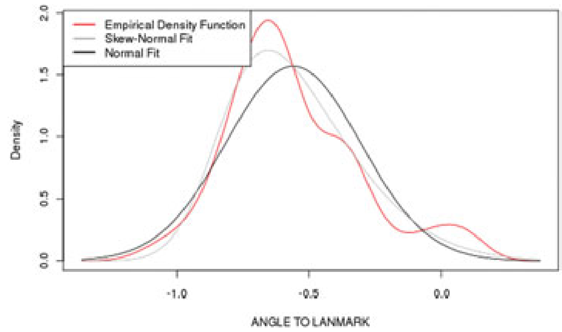
3.3. *Median manoeuvre plans*. The identification of the manoeuvre sequence and its parameters in combination with identification of navigational aids for turn

Table 6. Statistical parameters for angle (rad) to navigational aid at turn initiation. Angle defined positive in counter-clockwise direction.

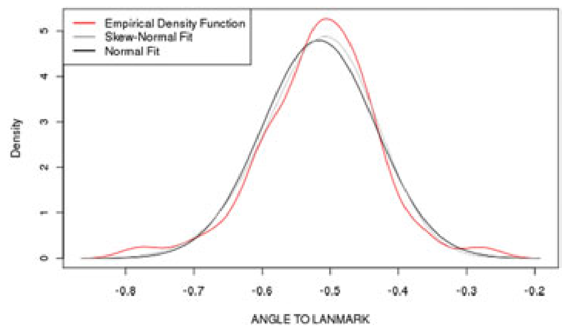
Traffic group, section	Navigational Marking	Distribution parameters		
		Location	Scale	Shape
"North 2", section 2	Flatholmen	5·01	0·24	−0·700
"North 4", section 3	Nesjaflu Lysbøye	−0·84	0·38	2·710
	Nesjaflua	−0·45	0·11	−1·253



(a) Flatholmen, relative frequency 1.0



(b) Nesjaflu Lysbøye, relative frequency 0.686



(c) Nesjaflu, relative frequency 0.245

Figure 12. Angle to most probable navigational aid at initiation points.

initiations makes it possible to formulate a template navigational plan for the observed traffic by substituting observed mean values for manoeuvre parameters and angle to navigational aid at turn initiations. The manoeuvre plans are seen in Table 7 for "North 2" and Table 8 for "North 4". The turn sections in the harbour are omitted due to the uncertainty of turn radius and navigational aid. Turn direction in the presented plans can be inferred by the change in course angle and the apparent angle to the land marks are translated to the range $[-\pi, \pi]$. Course angles are positive in clockwise direction, while apparent angles to landmarks are negative in clockwise direction.

4. DISCUSSION.

The method outlined above is found to yield good results in normal navigation scenarios, while the accuracy in the inner harbour area is limited due to a very complex manoeuvring behaviour. In this case the harbour area

Table 7. Inferred mean manoeuvre plan for traffic-group "North 2".

Section	Manoeuvre Parameter	Mean Value
1	Course angle (rad)	0·32
	Speed (knot)	12·5
1 to 2	Transition condition	Angle (rad) to "Flatholmen" $< -1{\cdot}4$
2	Turn Radius (m)	1000
	Speed (knots)	10·2
2 to 3	Transition condition	Obtained course angle (rad) $> 2{\cdot}27$
3	Course angle (rad)	2·26
	Speed (knots)	8·6

Table 8. Inferred mean manoeuvre plan for "North 4".

Section	Manoeuvre Parameter	Mean Value
2	Course angle (rad)	−0·78
	Speed (knots)	11·0
2 to 3	Transition condition	Angle (rad) to "Nesjaflu Lysbøye" $< -0{\cdot}56$ Angle (rad) to "Nesjaflu" $< -0{\cdot}51$
3	Turn Radius (m)	1190
	Speed (knots)	11·5
3 to 4	Transition condition	Obtained course angle (rad) > 0
4	Course angle (rad)	0
	Speed (knots)	11·6

Table 9. Correlation ratio for cross-track offset, speed, course and curvature.

Group	"North"	"South"
1	0·0818	0·0706
2	0·1013	0·1299
3	0·131	0·0791
4	0·2081	0·1582

was close to the limit on accuracy afforded by a discretization in 75-by-75m bins and the capability of the manoeuvre model to represent the underlying mechanisms of ship traffic. Another effect that was experienced in the harbour area was the drop in accuracy of the curvature calculations near the end of the time-series, due to an increasingly shorter filtering distance. This effect is exaggerated by the location of the time-series ends in the high curvature region associated with turn manoeuvres.

The model's assumption, that the parameters of the traffic statistics and the manoeuvre plan can be calculated independently, is tested by computing the correlation ratio of the parameters. The correlation of cross-track offset, speed, measured curvature in turns and course angle in straight sections are given in Table 9. A value close to one indicates a high degree of correlation and values close to zero, a low degree of correlation. From Table 9 it is evident that the correlation increases with the complexity of the manoeuvre, but even the most complex manoeuvre sequence has a relatively low correlation ratio. This could be explained by the ability of the human operators on the vessels to adapt to the situation and successfully eliminate undesirable conditions and obtain the desired future state of the vessel. The low degree of correlation supports the assumption that manoeuvres can be treated separately and the error introduced by doing so will be small. The viability of AIS as a data source appears good, as the number of cases compensates for the lack of accuracy with regards to simulation trials. The large number of cases in the densest traffic-groups also lends credibility to the statistical description and the measured median values.

5. CONCLUSIONS.

We have shown how automated grouping of ship traffic can be achieved and how it can aid in providing a large sample size for analysis of ship traffic. The methodology presented makes few, if any, assumptions about the behaviour of the traffic in the area and does not utilize any prior knowledge about the traffic pattern and produces good results in the vicinity of a harbour. The combination of automated grouping and the availability of AIS data opens up a range of possibilities for analysis of ship traffic and manoeuvring from simple statistical studies of current traffic to the inference of a prototypical voyage plan for a group of ships. However the method is dependent on recognizable patterns in the traffic in an area and it will not detect traffic patterns where none exist, but it has the potential to be of great aid to traffic and manoeuvring analysis.

6. SUGGESTION FOR FUTURE WORK.

This paper has presented a method for almost automatic estimation of manoeuvre patterns from AIS. A natural progression from this work would be to apply these results to provide manoeuvre plans to faithfully simulate the traffic in an area. What is missing from this paper is a fully probabilistic definition of the simplified manoeuvre plan. Median values provide a suitable description of the traffic in the area as a whole. To apply the probability distributions derived for the manoeuvre parameters in Monte-Carlo style simulation studies there should be a procedure to translate a probability level into a coherent set of manoeuvres, introducing an effect of semi-random plans to the simulation. Such a formulation will enable the study of the effect of highly improbable manoeuvre plans.

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Computer Vision and Ship Traffic Analysis: Inferring Maneuver Patterns From the Automatic Identification System

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Computer Vision and Ship Traffic Analysis: Inferring Maneuver Patterns From the Automatic Identification System

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ABSTRACT: The Automatic Identification System has proven itself as a valuable source for ship traffic information. Its introduction has reversed the previous situation with scarcity of precise data from ship traffic and has instead posed the reverse challenge of coping with an overabundance of data. The number of time series available for ship manoeuvring analysis has increased from tens, or hundreds, to several thousands. Sifting through this data manually, either to find the salient features of traffic, or to provide statistical distributions of decision variables is an extremely time consuming procedure. In this paper we present the results of applying computer vision techniques to this problem and show how it is possible to automatically separate AIS data in order to obtain traffic statistics and prevailing features down to the scale of individual manoeuvres and how this procedure enables the production of a simplified model of ship traffic.

1 INTRODUCTION

Analysis of ship traffic receives focus as the awareness of the risk it poses to the environment is increased. The analysis is not only motivated by the desire to quantify risk, but also to understand the effect of changes to the fairway and to propose improvements to harbor areas and inland waterways. Analysis of ship traffic has been hindered by a scarcity of data, requiring specialized installations or equipment for data collection. This scarcity has prompted studies that rely on synthetic ship maneuvering data from simulators (Hutchinson 2003) and (Merrick 2003). While simulator studies provides valuable insights, through high sample rates, controlled environment and absence of noise, they make compromises on either the number of passages with the use of human operators in full-mission simulators, or on accuracy by eliminating the human element and relying on fast-time simulators with autopilot algorithms.

We will in this paper show how the introduction of the Automatic Identification System (AIS) for ships can help in both providing a readily available data source for traffic analysis, and how analysis of this data can be employed to generate statistics of traffic conditions, estimate maneuver plans and parameters as inputs to fast-time simulator studies

The use of AIS in marine traffic analysis is not a new concept. (Gucma 2007) used AIS data to estimate the occurrence of accidents in the Baltic Sea by identifying the major traffic flows using AIS records of journeys. Little work has been done to apply AIS to analysis on the scale of maneuvers in a smaller or constrained area to derive the exhibited maneuver patterns. The area around the harbor of Risavika in southwestern Norway was selected as a case study. This area was selected since the presence of island formations and the coastline should impose a structure on the ship traffic. Information about all the navigational markings in the area was obtained from the Norwegian Hydrographic Service and contained data for position, type and identifiers for all publicly maintained navigational aids in the area. The area with AIS position reports and navigational markings indicated is shown in Figure 1.

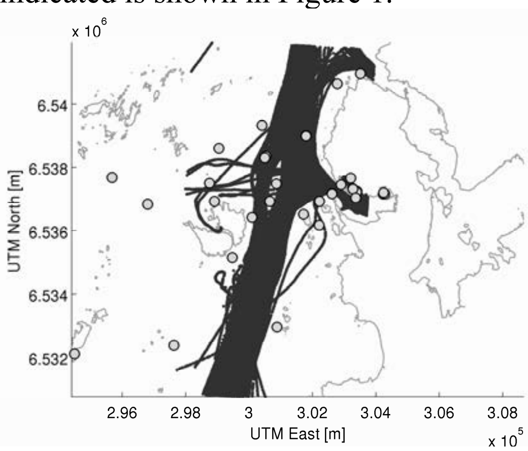

Figure 1: Risavika harbor with AIS position reports and navigation markers indicated

The small-scale analysis benefits from the large volume of data available, but the size of the data sets involved makes analysis more demanding. At this level the analysis method must take into account the alternate routes through the area and the possibility of harbors.

The introduction of AIS has replaced the previous scarcity of ship traffic and maneuver data with an overabundance. Whereas one previously had to construct limited shore based measurement systems with limited lifespan or rely on data from a selected set of vessels with logging equipment, AIS provides a continuous stream of information of the position and speed all AIS enabled vessels in range. The system provides position and speed updates on predefined intervals depending on vessel speed and maneuver situation with a sample-rate varying from 3 seconds for high speed or turning vessels to 15 min for ships at anchor. The instantaneous information density varies naturally with the traffic density of the area, but if one considers past data, the amount of information to be shifted through and analyzed is considerable. The ability to analyze, and the capabilities of the techniques employed, will determine the quality of information about ship traffic extracted from this new source of historic ship traffic data.

On this background we present a method based on computer vision techniques, which is capable of handling this increase in available data.

2 METHOD

Analyzing ship traffic is a two-stage process where the first task is to transform the collected data into a form that eases the final analysis. A method for transformation of AIS data frames to a collection of maneuvers presented is comprised of following stages:

- Reconstruction of vessel specific time-series from AIS data
- Sorting of time-series from geometric similarity of the position trace
- Subdivision of the geometric similar groups into groups with the same direction of travel

This process produces groups of time-series with similar maneuver patterns and direction of travel well suited for generation of statistics and further analysis. Further analysis of these groups can include

- Traffic properties such as distribution of vessel velocity and spread
- Estimation of maneuver sequence and parameter statistics
- Estimation of the most probable navigation aid used for maneuver transitions

2.1 *Model for ship maneuvers*

The ship maneuvering process is represented as a sequence of basic maneuvers. The basic maneuvers are instantiated and appear as a recognizable maneuver pattern. The most basic subdivision of maneuver patterns is the distinction between constant course and course changing maneuvers. While these categories can contain variations in the strategies employed to obtain the desired result, the two groups are represents the simplest geometric model is the model ship maneuvering.

2.2 *AIS data collection*

Data frames from the Norwegian AIS stations in the area around the harbor of Risavika were collected for three months from April to June 2006. AIS data frames are marked with a time stamp and the vessel specific MMSI number and contains the vessels instantaneous position and speed if available.

The data was ordered by MMSI number and time to recreate the time-series for each vessel. The time-series was then split at significant discontinuities in time to handle the cases of vessels leaving the studied area or coming to rest in a harbor. The number of AIS position reports in the area was 512,533 and the position reports were reduced to 2763 time-series

2.3 *Grouping of time-series*

Application of image registration techniques solves the laborious task of grouping the time-series form the geometric similarity of the position trace.

Image registration techniques (Zitova 2003, Brown 1992) is applied in medical imaging and production control, and can be explained as the process of comparing images mathematically to produce an objective measure of their similarity and to detect the presence of a-priori known objects. These techniques are well suited for sorting vessel trajectories from their geometry as the position trace in isolation forms a line in an otherwise empty space. The trace of a vessels position can be transformed into the form of a digital image by discretization of the reported position. The studied area was dividend into 75x75m bins and the number of position in each bin was counted and stored in a matrix for each time series. This is the representation used for grayscale images in image analysis.

Application of image registration must account for the possible differences in image resolution, rotation and translation of the captured scene. These parameters are controlled due to the transformation of remotely sensed data into an image with controlled orientation and resolution, but the location of the imprint of the individual vessel traces introduces an unknown possible translation. An application of image registration to group geometric similar tracks must account for this displacement within each group, but a global compensation will introduce errors, as it will detect similar position traces of similar form, but of very different location.

To reduce processing time the sorting of position traces was divided into a coarse and detailed analysis. The coarse analysis simply looked at the correspondence of track images without accounting for possible translations. If two images were deemed similar, future comparison was done with the mean track of the two. The coarse analysis left a large number of small groups, which were used as inputs to the detailed analysis. The detailed analysis made use of numerical optimization to find the optimum level of similarity between the groups. The cross-correlation between two images, where one has a translation (u,v) in (x,y) direction was used as an objective function and is seen in Equation (1).

$$CCR(u,v) = \frac{\sum_x \sum_y T(x,y) \cdot I(x-u,y-v)}{\max(\sum_x \sum_y T(x,y), \sum_x \sum_y I(x-u,y-v))} \quad (1)$$

Where T=reference image matrix and I=the test image matrix with translation (u,v). The cross-correlation defined in Equation (1) is only valid for integer values (u,v) so a 3D interpolation method from (Vetterling 2007) was implemented to provide a continuous formulation of the cross-correlation. The interpolation routine allows standard numerical optimization strategies, such as steepest descend, to be applied to find the maximum correlation between two images. The cross-correlation was used to refine the grouping obtained by the coarse method by an iterative process where groups which showed a maximum correlation where combined.

The final operation on the sorted time series was to split each geometrically similar group into direction specific groups by considering the angle between the start and end points of each time-series.

2.4 *Group maneuver identification*

The time-series reconstructed from AIS have heterogeneous sample rates, within the geometric similar group, and even within the individual time-series. This necessitates a transfer of individual time series data to a common representation, which compensates for the variations in sample-rates. The properties of the time series group was estimated from 100 evenly spaced control points. The control points were computed as the mean points of 100 evenly spaced points for each time-series belonging to the group. Mean perpendicular vectors to the mean path were calculated in conjunction with the control points and used to establish mapping of the time-series indices to the control points by finding the intersection between the time-series trace and the perpendicular vectors.

The sequence of maneuvers in a group was tracked by the curvature of the vessels trajectory. The curvature of the vessel trajectories in each time series was computed by considering the x and y coordinate as signals in the time (Aarsæther 2007) as seen in Equation 2.

$$\kappa = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\left(\dot{x}^2 + \dot{y}^2\right)^{3/2}} \quad (2)$$

A polynomial was fitted locally to the x and y signals in time to provide well-defined derivatives for curvature calculation. The curvature of each time series was transferred to the group by the index to control point mapping. The group curvature is then calculated from the median of the group curvature at each control point. The individual turn and straight sections of the group are identified by an ad-hoc two-stage filtering based on statistics. The mean value, μ, and standard deviation, σ, are calculated and the points of the group curvature curve that falls outside the region defined by $\mu \pm 2\sigma$ are defined as belonging to a turn section, μ and σ are recalculated for the remaining points and the process repeated once more. Contiguous regions are identified as turn and straight segments.

The indentified turns in the group curvature only provide information about the median straight and turn behavior, to extend the analysis to the parameters of the maneuver model and to provide statistics demands data for the identified sections from each time-series. The translation between the turn sections of the median path to the individual time series is not well defined as the map of positions to control points. Variations in curvature can occur at different positions along the path and it is the sequence of maneuvers that is of interest. The turn sections of the median curvature were isolated and transferred to an image representation using the same procedure as for the position trace. The image representations of the individual turn sections were then matched to a section of the time-series by optimization of the similarity between the turn image from the group curvature and the time-series curvature. This identifies the locations of the turn sections in the individual time-series and enables the extraction of statistics based on the maneuver progression of the individual vessels instead of relying on geometric areas or indices from the group curvature to extract data.

2.5 *Statistics of time-series groups*

Statistics for each time-series group was calculated at the intersection between straight ant turn sections. The sections of the individual time-series sections were transferred to the group sections by mapping the turns in a time-series to the corresponding turn numbers in the group. Variables were according to section type

- Turn section: extreme, median & mean curvature and median speed over section
- Straight section: average course angle over section, offset from median path at both endpoints and median speed over section

2.6 *Identification of navigational aids*

The identification of the most used navigational aids is dependent on the location of the border points between the straight and circular sections of the ships path in relation to the navigational markings in the environment.

The identification of the most probable navigational aid is more error prone than processing of AIS data since the result is directly influenced by the choice of criterion used to identify the aid used in each time-series. The identification criterion used is based on ship-handling theory, where navigation references are preferred if the bearing from the turn initiation point to the reference is close to parallel with the future course. The angle to all the navigational markings in the area was calculated for each turn initiation, and the marking with a bearing closest to the course at the turn exit was chosen as the most navigation mark in use.

3 RESULTS

The entire collection of AIS data frames was stored in an SQL database for easy management and extraction. Data frames was selected according to area and ordered by time and MMSI number. The image registration routines and data processing was implemented in MATLAB. The time-series was converted to images with the *hist3* function of Mathworks' "statistics toolbox" for MATLAB, and optimization of image similarity was handled by the constrained optimization function *fmincon* from "optimization toolbox" with gradient descend search.

3.1 *Separation of traffic*

Traffic clustered in seven groups, in addition groups consisting of one to five time-series was also present, but these have lack the numbers required to proclaim them as traffic-groups. Of the seven major groups one group consisted of AIS position reports of vessels at anchor in the harbor and was excluded from further analysis. The number of time-series in the other six groups, as well as the breakdown in directional groups, is seen in Table 1

Table 1. Distribution of time-series into groups of geometric similarity

Group	Total	Direction 1	Direction 2
1	1017	443	573
2	809	436	373
3	76	16	60
4	552	240	311
5	17	4	13
6	11	2	9

The geometric group of time-series belonging to the five first groups is seen in Figure 2-6. Time-series group six is excluded since it is only a small component intersecting with the areas northeast corner.

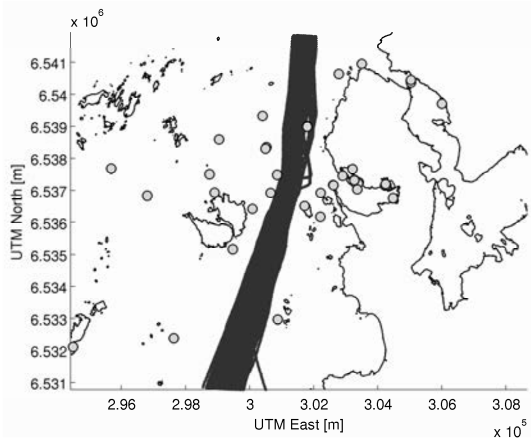

Figure 2: Position trace of time-series in group 1

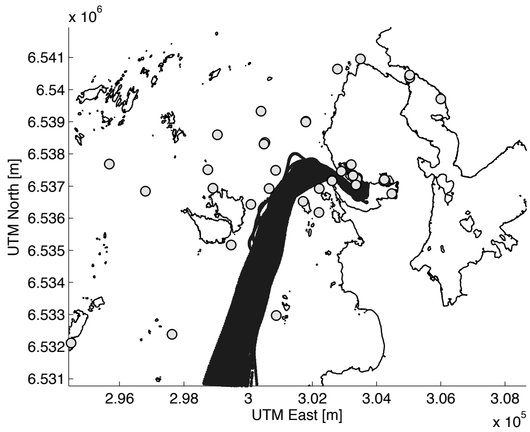

Figure 3: Position trace of time-series in group 2

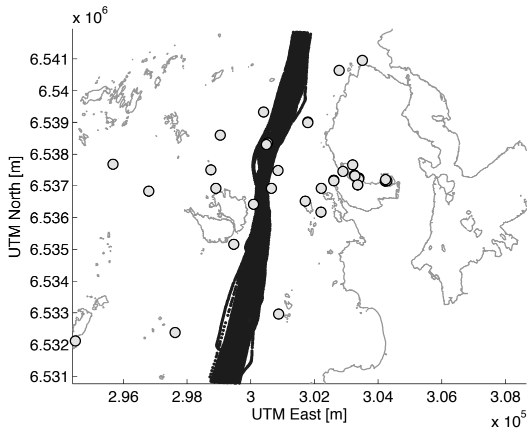

Figure 4: Position trace of time-series in group 3

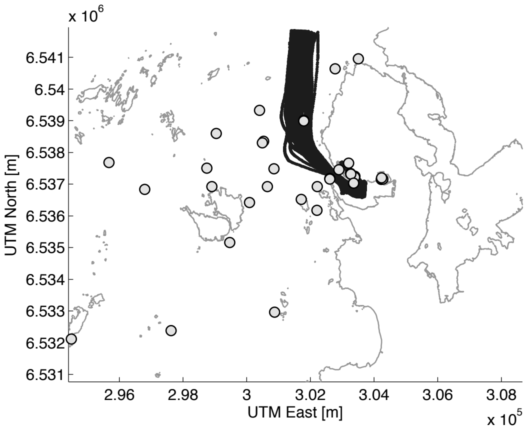

Figure 5: Position trace of time-series in group 4

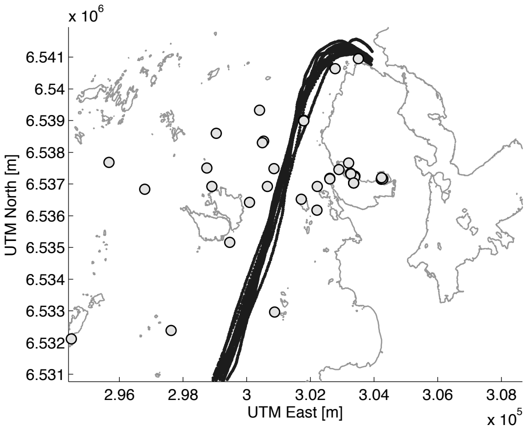

Figure 6: Position trace of time-series in group 5

For further analysis based on statistics, only the three densest populated geometric groups should be considered. This is due to the uncertainty associated with statistical analysis of small populations and to avoid drawing conclusions on a weak statistical base.

3.2 *Maneuver sequences and statistics*

Maneuver sequences were identified and statistics for traffic properties and maneuver parameters were produced. The measured variables were fitted both to the normal and skew-normal (Azzalini 1985) probability distributions. The skew-normal distribution was introduced to compensate for expected skewness in the data that could severely influenced the accuracy of the normal fit. Statistic calculations and fitting of distributions was performed with "R" with the "MASS" and "SN" statistic libraries. The median paths with turn section border points indicated are shown in Figure 7.

Due to space limitations a full treatment is only possible for one direction in one of the sample groups. The direction group 1 of sample group 4 is analyzed further. The parameters of fitted skew normal probability distributions of the traffic parameters are shown in Table 2.

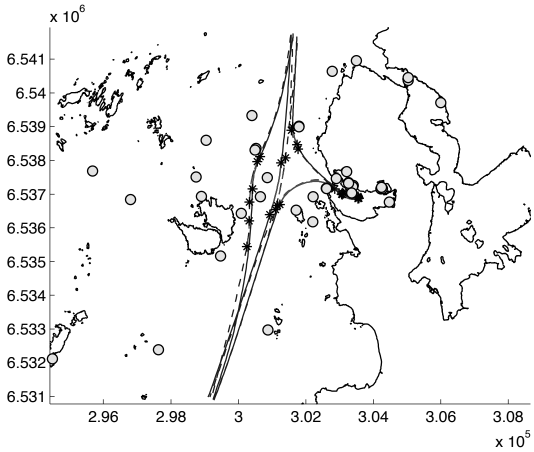

Figure 7: Median traffic paths with turn sections indicated.

Table 2. Parameters for traffic statistics for group 4, direction 1

Section	Type	Variable		Location	Scale	Shape
1*	Turn	k.ext	[1/m]	-5.20e-4	2.75e-3	-14.6
		speed	[kn]	5.5	3.42	3.05
2	Straight	offset start	[m]	19.7	37.3	-1.13
		offset end	[m]	-37.5	64.6	0.85
		course	[rad]	-0.90	0.08	1.89
		speed	[kn]	7.9	3.7	2.51
3	Turn	k.ext	[1/m]	-4.21e-4	7.36e-4	-9.34
		speed	[kn]	8.3	4.15	3.12
4	Straight	offset start	[m]	-100.4	155.0	1.74
		offset end	[m]	-120.6	163.9	2.36
		course	[rad]	0.012	0.053	1.18
		speed	[kn]	8.5	4.30	3.48

* Start section inside harbor

From Table 2 it is possible to track the increase in both the vessel speed and spread from median position from the harbor area to the edge of the studied area. The curvature of the turn sections shows that the course-changing maneuver in section 3 can be modeled as a turn-circle maneuver with a radius of approximately 1.25 nautical miles.

The goodness of fit between the data from the AIS time-series and the skew-normal probability distribution function can be seen in Figures 8-10 where the empirical density function is plotted together with the fitted distribution functions.

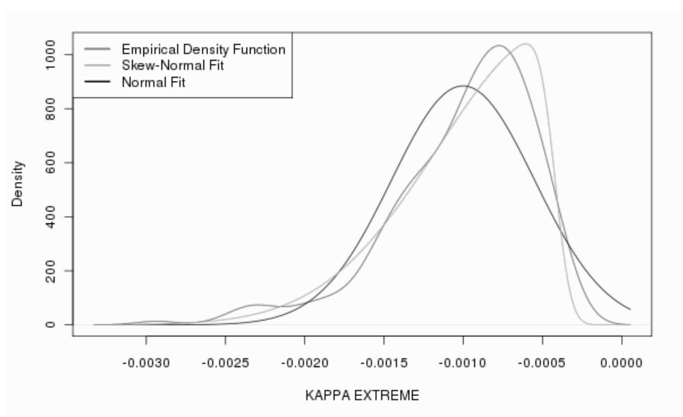

Figure 8: Extreme value of curvature during turn.

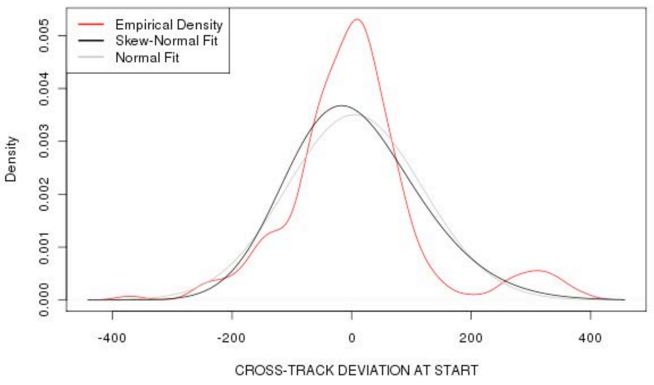

Figure 9: Offset from median position at end of turn (start of next section)

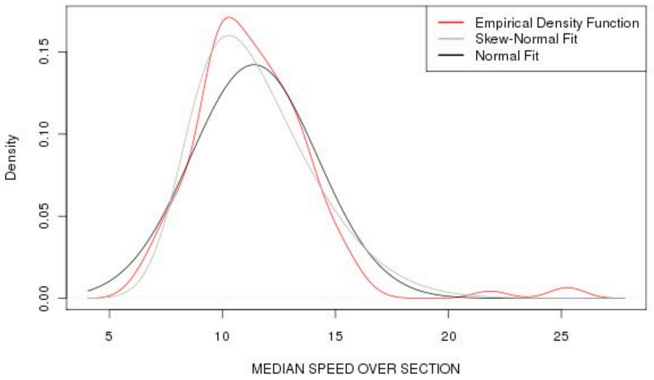

Figure 10: Median speed over turn section

3.3 *Navigational aids*

The identification of navigational aids made use of the information of navigational markings in the area as provided by the Norwegian hydrographic Service, but excluded markings consisting of iron poles used to mark shallows. This left only lighthouses and light buoys. Identification showed good consistency with only two to three objects contributing the majority of observed identifications. For the initiation of the turn in section three seen in Table 2 the relative contributions are shown in Figure 11

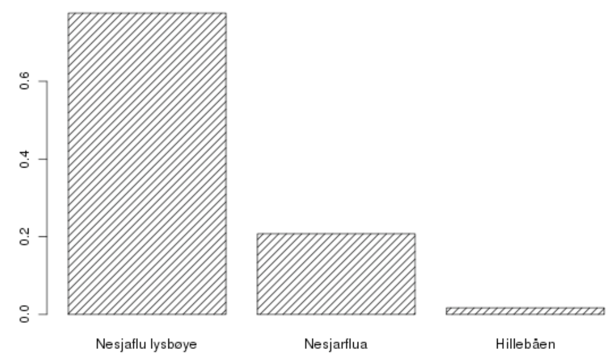

Figure 11: Relative frequency of identified used navigational aid

From Figure 11 it is apparent that the navigational markings at the location "Nesjaflua" dominates as the most probable navigational mark. The distribution of course angles between the two most used markings is seen in Figure 12, the overlapping notches in the plot indicates that there is no statistically significant difference between the median apparent angle to the markings.

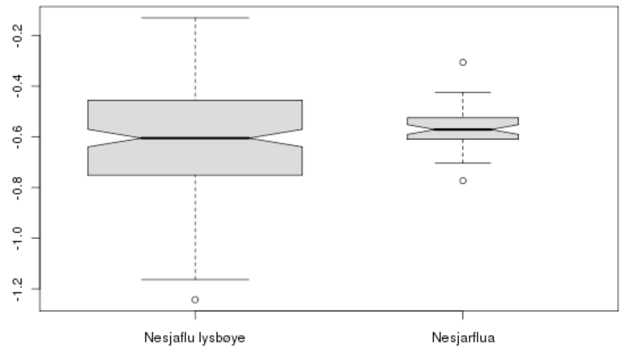

Figure 12: Distribution of apparent angle to landmark, box width indicates sample size.

4 CONCLUSION

It has been demonstrated that image registration techniques can provide an efficient and accurate solution to the problem of shifting through large amounts of position reports from AIS and prepare them for analysis in groups. Image registration also overcomes the problem of identification of turn maneuvers in individual time-series. The group analysis of the AIS position reports enables the identification of statistical parameters for the traffic flow, as well as of probable navigational marks for turn initiations and turn radi.

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Adding the Human Element to Ship Manoeuvring Simulations

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Adding the Human Element to Ship Manoeuvring Simulations

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Time-domain simulation of ship manoeuvring has been utilized in risk analysis to assess the effect of changes to the ship-lane, development in traffic volume and the associated risk. The process of ship manoeuvring in a wider socio-technical context consists of the technical systems, operational procedures, the human operators and support functions. Automated manoeuvring simulations without human operators in the simulation loop have often been preferred in simulation studies due to the low time required for simulations. Automatic control has represented the human element with little effort devoted to explain the relationship between the guidance and control algorithms and the human operator which they replace. This paper describes the development and application of a model for the human element for autonomous time-domain manoeuvring simulations. The method is applicable in the time-domain, modular and found to be capable of reproducing observed manoeuvre patterns, but limited to represent the intended behaviour.

KEY WORDS

1. Human factors. 2. Ship manoeuvring. 3. Fast-time simulation.

1. INTRODUCTION.

Time-domain simulation of dynamic systems has increased in popularity along with inexpensive computer power, simulation suites and the availability of time-domain models of complex systems. Time-domain system formulations are attractive due to the pervasiveness of specifying systems with differential equations in the time domain and the ease of implementing performance prediction, design and exploratory analysis. Time-domain simulations of ship manoeuvring have traditionally been applied in design of automatic control systems, performance prediction of ships and crew training. As the capabilities of computer hardware and simulation software have increased, application of Monte-Carlo style analysis has become feasible in risk analysis of ship manoeuvring and traffic patterns. Synthetic simulation studies are attractive and sometimes necessary as they allow low-cost investigation of system dynamics and offer a way to explore the effects of planned changes to systems and the environment.

Probabilistic safety assessment as a frequency domain application is limited to static operating conditions or to a predefined sequence of events. But ship manoeuvring is a process where the evolution of the ship's trajectory is highly dependent on the actions on the bridge and the environment; conversely the position and orientation of the ship can necessitate a set of actions required from the bridge crew. The dynamics of ship manoeuvring from the effect of control and environmental forces is modelled based on "*first principles*" understanding of mechanics in the time-domain. This formulation has been applied to generate data for frequency domain analysis. Such application of time-domain simulation of ship manoeuvring can be separated into real-time and fast-time studies, while the purpose of both is to derive a quantitative description of the risk, either by direct estimation from simulation results, or by expert opinion based on experiences from the simulation studies.

Simulator training of crew is a special case of real-time simulations where the aim is to expose and train the operators for new operations and rarely encountered situations. These simulations are employed in exploratory analysis where the performance or perception of the human operator is of primary importance. Examples of such studies include assessment of the effect of changes to the fairway (Hutchison, 2003) and measurement of crew response times (Chen and Moan, 2004). The drawback of real-time simulation studies is inherent in its name; simulations progress with the speed of the wall-clock, crew and simulator facilities are a limited resource and the effort required to undertake extensive studies is considerable. This has led to the application of fast-time simulators (Hutchison, 2003) where the human element is replaced by a combination of navigation and control algorithms. This substitution enables the time-compression of the simulation to be increased to the upper attainable limit for the combination of computer power and model complexity. This allows fast-time simulations to serve either as an inexpensive screening process for real-time simulation studies, or as an inexpensive desktop simulator experiment. While the numbers of accidents and lost vessels are stable or showing a slight decrease (Soares and Teixeria, 2001), there has been a profound shift in the attribution of the root causes of accidents towards human actions, either as an isolated element on the bridge, or as a part of the wider socio-technological system that designs, builds and operates the ship (Hollnagel, 1998). There are numerous models for human performance ranging from simple time response models to models of human cognition and elaborate information processing models. This plethora of models illustrates both the increased focus on the human element and the ambiguity of resulting description where multiple models describe the same process. While a large effort has been expended in the area, recent developments show their strength as explanatory tools for use in psychology or retrospective analysis, but possess limited predictive powers. This situation presents a dichotomy in the use of fast-time simulation in risk analysis where the simplifications necessary to exploit the advances in dynamic system models and computer power, also remove the element most prone to errors and deficiencies. This situation persists since the integration of contemporary models of human operators is hindered by the heterogeneous model structures and lack of predictive ability. This results in simulations of systems that conform to the behaviour of computer controlled systems and that lack a representation of the dynamics and structural composition of the human element. It is evident that analysis of dynamic systems without considering the human element only answers questions of the system's technical abilities, not its actual performance and mode of operation of non-autonomous systems.

In this paper we will combine a human reliability model and time-domain simulations of ship manoeuvring and show how this approach can be implemented, and in turn simulated, to form a dynamic model that shares both the traits of the human operator and the dynamics of the vessel.

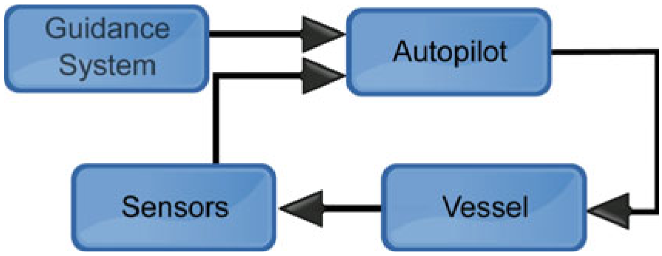


Figure 1. Ship manoeuvring in the context of automatic control.

2. SYSTEM DESCRIPTION.

Construction of system models for prediction and design verification is an integral part of engineering disciplines. The increase in available computer power has been crucial for simulations, training simulators and increasingly realistic simulations available in computer games. Whereas training simulators and computer games are constructed to interact with a human operator, Monte-Carlo style studies contain an implicit model for the human element.

2.1. *Vessel dynamics and autopilot systems.* Ship manoeuvring simulations rely on two theoretical fields: hydrodynamics and automatic control. Hydrodynamics describes the dynamic behaviour of structures in water under the effect of waves and current, while automatic control provides guidance and suitable inputs to make the vessel fulfil a manoeuvring objective, be it station keeping or trajectory tracking. Models for ship dynamics with scale models can be found in (Fossen, 2005), (Norrbin, 1971) and (Perez and Blanke, 2002). The equations of motions of the vessel are formulated as a set of first order differential equations. A typical system structure is seen in Figure 1, the formulation of the autopilot subsystem proceeds in a fashion where the combined system of the autopilot and vessel achieves reference tracking from the guidance system while repressing disturbances from the environment. The guidance system provides a reference-desired state to the autopilot which compares it to the actual state of the system and devises an appropriate response. A classical structure for an autopilot is the Proportional-Integration-Derivative (PID) control which stabilizes the system by a suitable mapping from the difference in the system state versus the desired state, the rate of change and the accumulated error to the system's control inputs. The PID formulation has been used successfully to design autopilots and to investigate the dynamic response of ships and has additionally been applied in risk analysis and fairway design studies (Hutchison, 2003). However this structure only accurately depicts the process of autopilot control and neglects the underlying method of ship manoeuvring where the human operator and automatic control forms a joint system, while automatic control is a necessity in fast-time simulations as it provides the mechanisms to control the dynamic system in place of the human operator. The direct and exclusive application of automatic control as a substitute for the human element lends little support to the final results as the element most prone to errors has been replaced.

2.2. *The bridge as a man-machine interface.* Studies of human performance and automatic control of engineering systems emerged when the performance demands and technical abilities increased beyond the capabilities of the human operator. The last 50 years have seen a dramatic increase in the complexity of power plants

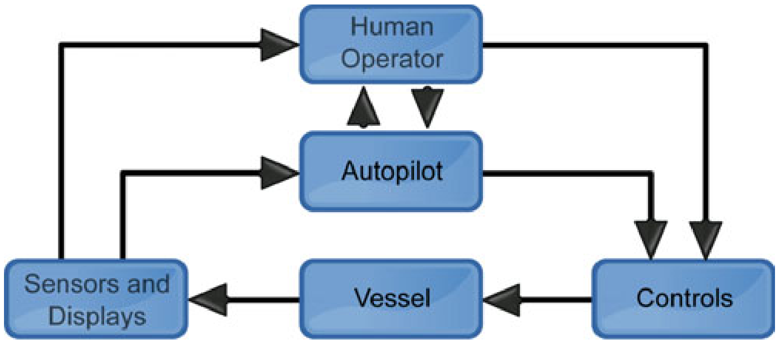


Figure 2. Ship manoeuvring as a joint cognitive, supervisory control model. The structure of the joint cognitive system is presented in (Hollnagel, 1998).

and transportation systems such as aircraft and ships. Ships have increased in size, speed and gained new propulsion and position control devices in conjunction with a trend of increasing automation, with a system configuration where the human operator occupies a supervisory role as seen in the joint system of Figure 2. The two main components in the system are the skills of, and the availability of plans and procedures to, the human operator. Both elements must be represented in order to construct a system model with exploratory power for analysis by simulation.

2.2.1. *Joint cognitive systems.* Neglecting fully autonomous vessels, ship manoeuvring involves the human element in the control loop. The human element appears engaged in manual control, but the operation of modern ships is accurately described as a joint system with the operator in a supervisory role. This system structure reflects the trend of increasing automation in transportation systems with the human operator responsible for high level planning and outcome with the automation system responsible for low-level operation. A typical example of the structure of such a system is depicted in Figure 2, which is an adaptation of the structure presented in (Hollnagel, 1998). This formulation poses a problem for use in manoeuvring simulations as the human operator will appear in the simulation loop leaving two options:

- Devise a suitable model for human performance.
- Use an actual human operator in the simulation loop and lower the time-compression to real-time.

Leaving the human element intact results in an expensive method which fails to take advantage of the possible time savings from an autonomous simulation, but autonomous simulations must include a model better suited to represent the operator than direct application of automatic control. The available models for the human operator originate in risk analysis, human reliability analysis and psychology and have not only inhomogeneous structures but also differ in system boundaries, a situation that impedes the exchange of ideas and theories between the disciplines.

2.2.2. *The human operator.* Developments of models of the human element have been motivated by the needs for more knowledge about reasoning and the cognitive interaction with the environment and the need to include human operators in operational analysis. The models from these two areas of study differ in their orientation

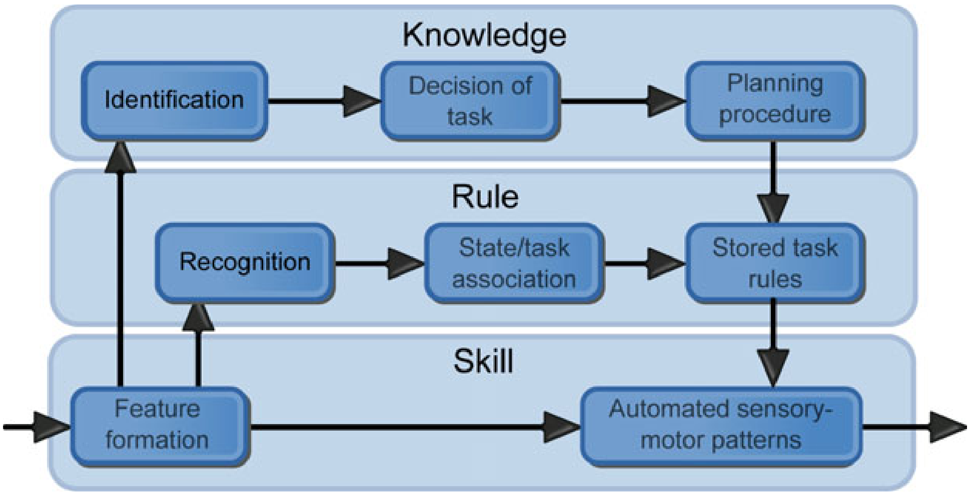


Figure 3. The step-ladder model of human cognition implied by the skill-rule-knowledge framework of Rasmussen, as presented in (Hollnagel, 1998).

in the time domain, analysis of the human brain proceeds backwards in time in order to explain "*why*" and "*how*" something happened while systems analysis is directed forward in time to explain "*when*" and "*how often*" something will happen (Hollnagel, 1998). The underlying model of human reliability varies from simple frequency of failure models (no underlying model of the human operator) to models with elaborate explanation of the underlying mental structure (over modelling of the human operator). The nature of human reliability analysis is that of indirect analysis by inferring mental activities and reasoning hidden from direct observation and places them into a cause-and-effect relationship with the observable result. Thus intentions behind, and causes of, the variation in human performance remain in the covert realm of the mind, while the resulting actions, intended or unintended are overt and possible to observe. One of the most influential models of the human operator has been Rasmussen's Skill-Rule-Knowledge (SRK) framework which divides the possible performance modes of the operator into three categories corresponding to level of familiarity and training:

- Skill: High level of familiarity, automatic translation of situation to actions
- Rule: Familiar procedures available, selection of the right procedure for execution
- Knowledge: Low level of familiarity, situation analysis required with formulation and selection of procedures

The SRK framework provides an information-processing model of the human operator with a step-ladder model that represents the flow of information between the different cognitive activities. The different levels of familiarity with the situation are represented by horizontal short cuts in the stepladder model bypassing higher cognitive functions. The internal processes involved in the different processing stages are seen in Figure 3. The one feature in models for human performance that is consistent across models is the importance of procedures and training. This is explicitly formulated as the cornerstone in the Skill-Rule-Knowledge framework of Rasmussen, a similar construct appears in both the HCR (Hannaman and Worledge, 1988) (different response times) and CREAM (Hollnagel, 1998) (different modes of control) methods. The development of simple success/failure system components to cognitive models has provided an explanatory model for the intentions behind the actions, but it is impossible to derive a realization due to the unknown ordering of the cognitive functions forward in time. The model for human cognition/performance that provides an internal structure to the cognitive process serves as a frame of reference for discussion and retrospective analysis and not a definitive description of the covert processes of the human operator. With a system model formulated in the time domain, a model for human performance that provides the frequency of success/failure is of little use if one attempts to answer questions like "*how will the spread of traffic be if influenced by environment and variations in human performance*" as the timing of actions are paramount when the system is formulated in the time domain. A model in the time domain should be able to represent the infinitely large sets of possible outcomes that are achievable by the simple timing of actions.

2.2.3. *Navigation.* The foremost process with a significant human contribution on a ship is navigation. The process itself is a demonstration of the interconnection of planning and execution. Navigation as the process of deciding the appropriate set of actions to arrive at a specific destination consists of several separate sub-processes. The theoretical model of navigation and way-finding as presented in (Chen and Stanney, 1999) has been applied as a structural framework for performance analysis of bridge crews during navigation and ship manoeuvring (Gould et al, 2009). The model separates the processes required for successful navigation into three layers:

1) Cognitive mapping, internalized representation of the environment.
2) Decision-making process, evaluation of the environment and the formulation of strategies and plans required to arrive at the destination.
3) Decision-execution process, translation of the navigational plan into decisions and actions.

In transportation systems, such as ships and aircraft, the actions or strategies used are determined by the capabilities of the operator in conjunction with the available support systems of the vehicle. Transportation systems where the capabilities surpass those of the operator apply the notion of basic manoeuvres that can be combined into a navigational plan. The operator is trained in the execution of these manoeuvres and this representation is desired instead of an ad-hoc approach and provides a firm structure for activities such as planning, training and execution. In the context of sea transportation, ship masters and pilots develop a familiarity with the environment during their certification procedure for a particular area. Navigational plans for the area are also developed as a part of the certification procedure (Lützhöft and Nyce, 2006). The internalized representation and plan formulation is assumed to be completed or derived from other sources, leaving the decision execution process for the human operator in the joint cognitive system.

2.3. *An on-line human operator model for autonomous simulation.* The framework for modelling and simulation presented in (Zeigler et al, 2000) is used as a frame of reference when formulation of systems and components are discussed. The framework provides a tiered system which describes an increasing knowledge of system outputs in response to inputs and internal state transitions in the levels of system specification. The level of system specification is described in Table 1 where the amount of information available increases in the top-down direction. The relation between this framework and mathematical modelling of dynamic systems can be seen in the two different approaches to systems modelling, first principles and system

Table 1. The hierarchy of system specifications outlining the available information and what can be represented in a simulation.

	Level of System Specification	Description
1	IO Frame	Information about what crosses the system boundaries
2	IO Relation	Information about which input signals to expect with a defined input signal
3	IO Function	Information about what signal to expect from a input signal when the system is in a known initial state
4	IO System	Information about how the systems internal state trajectory evolves with the input signal and how the state and input signal combine to form the output
5	Structured IO System	Information about the subdivision of the possible values of the input, output signals and state into variables
6	Coupled IO System	Information about the coupling between the input and output signals and the internal structure of the systems state space, transition and output functions

identification. System identification techniques use knowledge or measurements of the input and output signals of a system to determine a system with an *a-priori* known system structure that exhibits the same dynamics in response to the input signal; this procedure places the system model at the level of the IO-relation level. The addition of an initial state establishes a one-to-one mapping between inputs and outputs and shows replicative ability and at the IO-function level. Models based on first-principle are formulated from a position of increased knowledge, particularly the response of system states to input signals. These formulations are at the structured IO system level where the permissible values of the state, input and output functions are known as well as how these contribute to the overall behaviour of the system. It follows directly that a modular model of differential equations with coupling from input to output shows a system at the coupled IO system level. A system on the IO system level is fully specified by:

- T is the time base
- X is the set of all permissible input values
- Y is the set of all permissible output values
- $\omega \subseteq \Omega$ is the set of all permissible input signals
- Q is the set of states in the system
- $\Delta: Q \times \omega \rightarrow Q$ is the state transition function
- $\Lambda: Q \rightarrow Y$ is the output mapping function

An additional system theoretical element from (Zeigler et al, 2000) is the morphism and homomorphism concept, which describe the similarity between systems and establishes a set of conditions to check if a simplified (small) system is a valid derivation of a complex (big) system. The morphism is used to establish the validity of simplified models in relation to complicated base systems and models as well as ensuring the correct representation of the model by a simulator algorithm. A morphism between a small system S' and the big system S is a set of functions g, h and k such that:

- g: $\Omega' \rightarrow \Omega$ encodes the permissible signals $\omega \in \Omega$ of the small system into the signals $\omega \in \Omega$ permissible in the big system
- $h: Q \rightarrow_{onto} Q'$ where $\bar{Q} \subseteq$ Q, h maps the subset $\bar{Q}$ of the big state set Q onto the small state set Q'
- $k: Y \rightarrow_{onto} Y'$ maps the output values Y of S onto Y' of S' for all $q \subseteq Q$ and $\Omega\omega' \in \Omega$.

The morphisms between two systems must conform to the following two criteria:

- *Transition function preservation:* $h(\Delta(q,g(\omega')))=\Delta'(h(q),\omega')$, a mapping of the state $Q\rightarrow_{onto}Q'$ where the big system receives an encoded $\omega=g(\omega')$ and undergoes a state transition $\Delta(q,g(\omega'))$ is equal to the same transition in the small system $\Delta'(h(q),\omega')$ with a state $q'=h(q)$
- *Output function preservation:* $k(\Lambda(q))=\Lambda'(h(q))$, a mapping of the output of the big system $\Lambda(q)$ is equal to the output of the small system $\Lambda'(q')$ with a state $q'=h(q)$

The morphism concept has practical implications for derivation of models from detailed base systems and further simplification of existing models as it imposes requirements on the derivation or simplifications of state space, transitions, admissible inputs and output behaviour:

- The mapping of the state space between S and S' ensures that an aggregation or simplification of the state space still retains some of the original structure and explanatory power
- The transition function preservation ensures that some of the behaviour in S is found in S'. S' cannot undergo state transitions that are not evident in S, but does not necessarily have to reflect all the state transitions possible in S
- That there is a correspondence between input signals and behaviour of the two systems. The system S' cannot accept inputs that are incompatible with the system S.
- If both systems receive corresponding input signals, they both undergo a state transition and the resulting output must also be in correspondence. The internal behaviour of S' must be uniquely mapped into the output of S. The converse is not true as the output of S' can represent a set of internal behaviours in S.

It is straightforward to show that the ship dynamics coupled with models for the response of steering machinery and the effect of lifting surfaces as presented in (Norrbin, 1971) is an example of a morphism between an infinitely complex real-system to a small system of selected physical variables. The real system has a larger state-space, but the identification of the simplified system parameters ensures that the system description fulfil the transition and output function preservation properties. A similar argument can be presented for different formulations of the manoeuvring problem. There is no corresponding argument for the relationship between the human operator and the model, as there is no model that is neither verified (consistent predictions) nor validated (predictive powers outside the base case). The system theoretical knowledge of the human operator is confined to levels 1 to 3 in Table 1, which implies that we can only hope to describe the system boundaries and at most arrive at a one-to-one correspondence between observed system inputs and outputs at the functional level.

3. A TIME DOMAIN REPRESENTATION OF THE HUMAN ELEMENT.

The learning process for pilots manoeuvring in confined waters described in (Lützhöft and Nyce, 2006) shows great care taken to establish a manoeuvre plan consisting of individual manoeuvres with transition points defined by available navigational markers. Passage plans are described as constant course

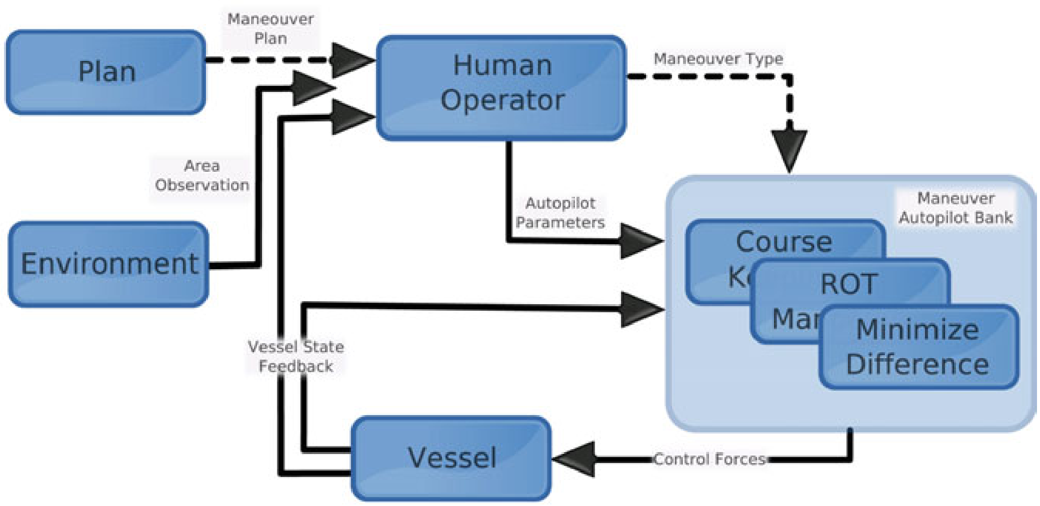


Figure 4. Guidance and navigation system configuration. The planning process is represented by a fixed plan of passage that references manoeuvre types. The transition between manoeuvres is controlled by the human element that observes the vessels relative position in the area and activates the corresponding autopilot with the proper set of parameters.

sections connected by transition on circle sections. The locations of prominent features and navigational markings in the area are used to estimate the location of the vessel in relation to the transition points. The plan relies on a set of clearly defined manoeuvre types utilized in restricted waters to control the future position and orientation of the vessel. This structure is utilized in the derivation of the human operator model with separation of planning as a static input to observation/decision and execution. Further decoupling of the decision and observation from the execution of the manoeuvre is possible by assuming that the operator is well trained in the manoeuvre set and thus will select the correct control strategy for each manoeuvre. The operator influences the vessel trajectory by deciding when the conditions to advance the plan are fulfilled by executing the next manoeuvre. (See Figure 4.) The internal structure of the implementation of the human operator model must not be confused with the structural validity presented in Section 2.3 since it is result of a formulation that suits the technical implementation.

3.1. *Observation-decision-response model*. The challenge when attempting to represent the human operator is to derive a coherent model for his actions even though there is a lack of understanding about the underlying mechanisms and causal relationships. The actions of others are observable and offer the only glimpse of the underlying mechanisms from individual introspection. This level of knowledge in the context of the levels of system specification from (Zeigler et al, 2000) presented in Table 1 is at the IO-relation level. This is at the IO-relation level since it is possible to observe a variation of responses to the same input signals which are recognized as an inherent feature of human performance. Time domain simulations frequently rely on simplified models for the system response due to hydrodynamic, structural and environmental forces derived from detailed base models, or identified from experiments. It is impossible to construct and validate a simplified time domain model by a (homo)morphic relation to a detailed base model for the human operator due to the absence of first-principles theories for human performance or even detailed empirical models. Instead of establishing a morphism relationship at a high level, the current

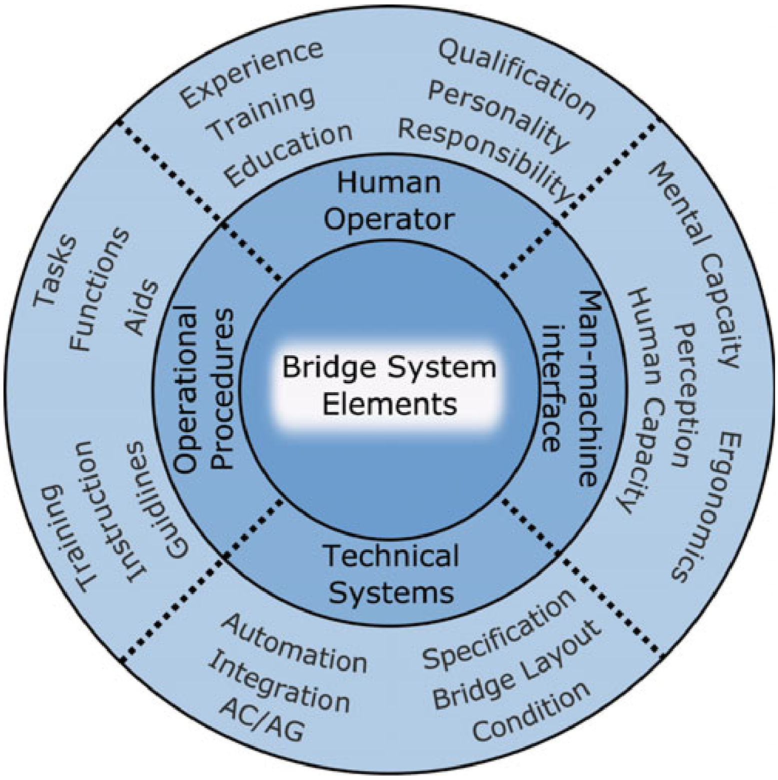


Figure 5. Schematic representation of the complete bridge system. The systems on the bridge are conceptually divided into groups representing the technical systems, the human capabilities, training and man-machine interface. The combination and interaction between these systems form the total system one can identify by thorough analysis a vessel bridge.

state of knowledge leaves the option of constructing a lower level morphism and then attempt to build from theory or experiments a system specification at a higher level. Since the coupling with the ship dynamics and environment is specified the admissible variables and the system boundaries are known and are at the structured IO-frame level. It would be impractical to attempt to account for all the possible interactions between the experimental frame (interacting system, in this case the environment and other vessels) and the possible interactions between the human operators on the bridge of the vessel. Such an attempt will inevitably lead to either an over-modelled complex system or a failure to capture all the possible interactions. The system boundaries for the human element are extended from the individual operator to the entire bridge including navigation equipment, autopilots and human operators. The focus is shifted from deriving the mode of the individual operator to a model which describes the interaction between the total bridge system (the operators, technical equipment, training and man-machine interface) and the mechanical properties of the vessel and environment.

The total system is depicted in Figure 5 and defines the areas encapsulated by the operator model. A model for the human operator which includes interaction between the individual operators, the possible interactions between operators, vessel systems and other vessels will quickly grow to an unmanageable size. This reduced representation leaves a well-defined system component interacting with the vessel and environment through observations, visual and electronic, of objects in the area and the state of the vessel & environment. The bridge system manipulates the vessel by changing the settings of the propulsion and control systems either by automatic or manual control. This results in the well-defined structured IO-frame:

- T is the time base $T=\{t \in \mathrm{R},\ t>t0\}$
- X is the input set $X=\{$*External Objects, Vessel State, Environment State*$\}$
- Y is the output set $Y=\{$*Rudder Commands, Engine Commands*$\}$

This choice of system boundaries represents a simplification as it eliminates the possibility of studying the individual and is thus only capable of producing a result as an aggregation of the underlying process. The presence of an initial state is needed to elevate the description of the bridge and human element to the level of the IO-function which provides an untangling of the one-to-many into a one-to-one description of system inputs vs. outputs. The selected system boundaries reduce the external manifestation of the vessels bridge activity to the time-to-action in comparison to an ideal case where the correct actions are executed at the precise time where they are required. In real conditions there is a variation in the timing of an action in the continuum "*too-early*" – "*too-late*". In the case of ship manoeuvring the strategy changes as the vessel traverses the plan of passage in the form of a sequence of manoeuvres. The transitions between the manoeuvres are determined by the vessel's relative position in the environment and the human operator's perception of this relation. The variability in human performance, environmental conditions and technological aids influence the accuracy in this judgment. An experienced and well trained captain will have an accurate perception of the vessel's relative position by combining reference systems and personal observations with experience, while a novice, or master unfamiliar with the area, may focus on a particular reference signal and misjudge or require time to confirm the position according to the passage plan (Findlay, 2006).

The time response curves applicable to the SRK framework from (Hannaman and Worledge, 1988) represent the effect of familiarity with the situation on the response time on the bridge in the time domain. From the SRK framework this corresponds to the different levels of cognitive processing required to formulate a response to an observation. The response curves are based on simulator experiments with human operators and are provided as a set of three parameter Weibull distributions for the response time. A logarithmic plot of the non-response probability ($1- P_{response}$) is shown in Figure 6. The response time is normalized by the median response time of the crew and the non-response probability is as seen in Equation 1 where t is the time available, $T_{\frac{1}{2}}$ is the median response time while βi, $C\gamma i$ and $C\eta i$ are the shape, location and scale parameter of the three parameter Weibull distribution for cognitive processing modes $i=\{$*skill, rule, knowledge*$\}$

$$P(t)=e^{-\left(\frac{(tT_{\frac{1}{2}})\cdot C_{\gamma i}}{C_{\eta i}}\right)\beta_i}. \tag{1}$$

A description on the IO-Function level is achieved by adopting a time-shifting mechanism for the transition between manoeuvres based on the response time formulation of (Hannaman and Worledge, 1988). The familiarity with the situation as skill, rule or knowledge together with a probability level serves as initial states to produce a one-to-one relationship between input and output signals in the form of different activation times of manoeuvres in response to the same observations. By

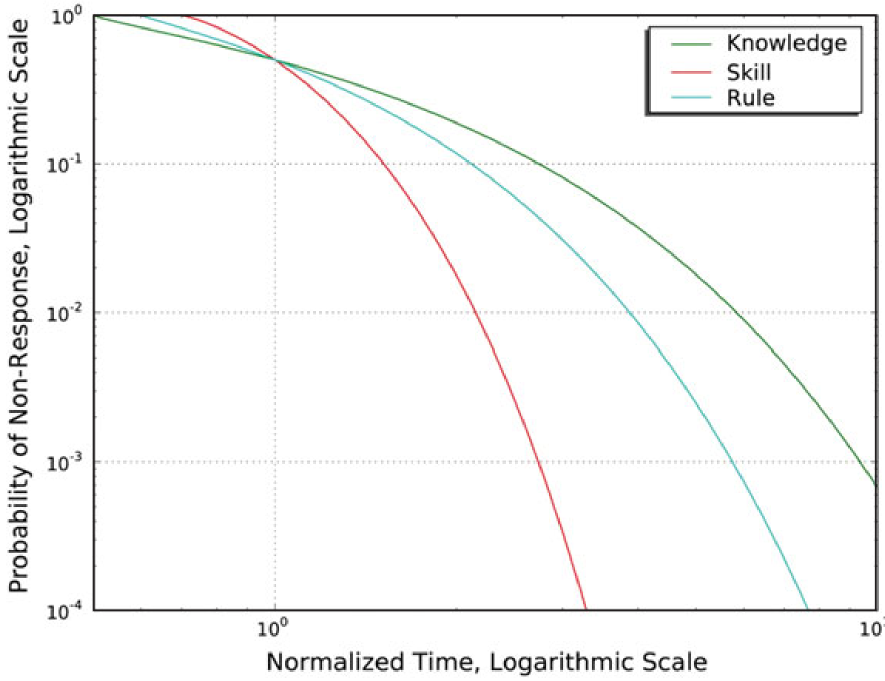


Figure 6. Operator time response probability curves form (Hannaman and Worledge, 1988) with increasing response time with increasing cognitive demands. Response time is normalized with the median response time $T_{1/2}$.

first defining the auxiliary time-shift function *Ftimeshift*: $P,\ i \rightarrow\ T$ with P as the selected probability level and i as the response mode and the *TESTPLAN*: $T,\ X,\ j \rightarrow\ T$ function to test the ideal transition time with regard to the manoeuvre plan.

$$t_{timeshift} = TESTPLAN + F_{timeshift} \tag{2}$$

It is evident that the time-shift function is the result of a state transition in the operator. This transition conforms to the conditions in Section 2.3 as the prescribed model of sequential manoeuvres necessitates the transition. It is therefore impossible for this formulation to undergo state transitions not in the detailed navigation model. In addition to the transition time, we must define the function MANEUVERPARAM: $j \rightarrow\ Y$, which provides the manoeuvre parameters of manoeuvre no j in the plan and the IO-function relation then becomes:

$$F{:}T, X \rightarrow\ Y = \begin{cases} if{:}t > t_{transition}, F = MANEUVERPARAM(j+1), j+=1 \\ if{:}t < t_{transition}, F = MANEUVERPARAM(j) \end{cases} \tag{3}$$

The model of the total bridge system receives a stream of observations of the area and activates transitions between manoeuvres when the orientation of the ship fulfils the conditions of the manoeuvre plan. The functional relationship between the fulfilment of the manoeuvre plan transition conditions and the response time completes the description of the human element with a delay action. The response of this system component is simply the activation of the next item in the manoeuvre plan.

3.2. *Plan and rules for navigation.* The navigational plan is represented as a nested binary list of basic manoeuvres. The structure allows for a branching pattern of manoeuvres, such as emergency manoeuvres or a cancellation path for the ship during the progression through the list. Each manoeuvre definition in the list contains:

- A manoeuvre type identifier, a set of parameters for the unique manoeuvre and specific observation conditions such as geometric parameters and anticipation of own ships future position by extrapolation
- A set of conditions directly related to the navigation area that specifies the conditions which the position of the ship must fulfil in order to progress to the next manoeuvre in the list.

The manoeuvre plans can be elicited from expert opinion or estimated from available ship traffic data such as in (Aarsæther and Moan, 2009). The manoeuvres are executed in a context and the manoeuvre plan therefore refers explicitly to the available navigational markings of an area. The manoeuvre plan must be specified in relation to these navigational markings to be capable of acting as a plan for the IO-frame relation described in Section 3.1.

3.3. *Execution.* Execution is the action from either the autopilot or the operator to translate the intention of a particular manoeuvre into commands to low-level control and machinery systems. The separation of planning, observation and decision from execution allows classic automatic control theory to be used to represent the execution of basic manoeuvres. The execution appears as commands to the underlying systems. With the selected system boundary the combination of autopilots and human operators on the bridge is anonymous with respect to the rest of the vessel. A list of specialized autopilots is used to represent the change in manoeuvre strategy in the progression through the list of planned manoeuvres. This formulation is extensible as it allows additional manoeuvre behaviours to be added later. The list of implemented manoeuvres for the autopilot is as follows;

- Course keeping, track a specific course to make the vessel follow a straight line.
- Elliptic turn manoeuvre, turn manoeuvre with control of the future track of the vessel which regulates the speed/rate-of-turn relationship to the curvature of an ellipse. Ellipse can represent a perfect circle, or a deformed circle (ellipse) due to cross-track offset of the vessel at the turn initiation point.
- Pass between two markers in the area, regulates the vessel to a imaginary line running perpendicular to the line joining two navigational targets in an area.
- Minimize difference between the apparent courses of two markers, regulates the vessel to an imaginary line that passes through two navigational targets. This manoeuvre emulates navigating after leading lights.

All autopilots are implemented as regular PID controls with suitable reference signals generated by associated guidance algorithms. The transition point between manoeuvres is located according to the geometric specification of the manoeuvre plan, but the dynamic behaviour of a vessel necessitates an earlier transition to allow the vessel enough time to either start turning or transition back to a static course. The distance from the ideal transition point in the manoeuvre and the actual transition point should be based on the dynamics of the vessel. The standard measure "*advance*" of the IMO turning circle manoeuvre is used to calculate the vessel transition point in relation to the ideal transition point. The individual vessel initiation point is placed a distance $d = advance - R_{turn}$ in front of the ideal transition point. The effect is achieved in the human operator implementation by introducing anticipation in the form of observing the environment at a position $d[m]$ in front of the ship.

4. RESULTS. The proposed model was implemented in Simulink as a block diagram together with the dynamic manoeuvring model for tankers from (Van Berlekom and Goddard, 1974). The model was complemented by a simple realization of wind forces for tanker ship profiles by applying the simple wind force formulation for a given wind speed and direction form (Aage, 1971). The overall system configuration was identical to Figure 4 with the addition of wind forces acting on the model. The manoeuvre area selected, motivated by convenience, was the same area used in (Aarsæther and Moan, 2009). The available navigational markings in the area were provided in machine readable form by the hydrographic service of the Norwegian Mapping Authority with position, name and type available for all markers. The area with navigational markers is seen in Figure 7 with the large concentration of navigational markers in the middle of the area being a harbour.

4.1. *Simulations*. Simulation experiments were conducted to test the ability of the system formulation to demonstrate replicative ability of manoeuvre patterns in the sense of the levels of system specification represented in 2·3. This investigation is divided into a test of whether the formulation is able to successfully navigate using a manoeuvre plan formulated in relation to the area, and if it is possible to replicate the full behaviour of traffic with the proper set of initial conditions.

4.1.1. *Manoeuvre plan*. The traffic pattern in the area as observed from AIS is seen in Figure 7. The manoeuvre plans of the area and initial conditions for the simulations are obtained from analysis of AIS data and the navigational markings in the area. The analysis produces a manoeuvre plan in the form of straight course sections interconnected by circular turns together with a set of navigational markers suitable for initiation of the turn manoeuvres. The traffic entering the area from the south and proceeding into the harbour was selected as a test case. The manoeuvre plan for this traffic section is seen in Table 2. Simulations conducted to illustrate the mean or median traffic in this passage plan has no need for initial conditions and manoeuvre parameters other than the mean values presented in Table 2.

4.1.2. *Traffic spread*. A statistical depiction of the traffic was generated as skew-normal probability distributions. To represent the spread of the traffic, the initial conditions for position and course are drawn from the skew-normal distributions with parameters from Table 2. A varying set of initial conditions is needed to replicate the traffic patterns of the recorded data. The initial condition is a triplet of positions in north/east direction and the course. In order to replicate narrowing spread of traffic during the approach to the harbour the positions of the vessels were sampled both at the initial point and at the transition to the first turn. A random course can then be calculated from a combination of any two points in the two bands. The end result is an initial condition that fulfils both the initial spread of traffic with course, but also the narrowing of traffic during the first manoeuvre. The spread of traffic along the initial plan section is preserved by sampling both the initial position and the position at the transition to the next manoeuvre. The sampling of the two distributions was conducted by selecting a random number in the range [0, 1] (uniform distribution) and solving the corresponding value for the cross track spread from the

Table 2. A sample manoeuvre plan as a sequence of straight course sections and circular turn manoeuvres. The plan combines objects in the area and the evolution of the ship state to formulate area dependent conditions for transition between manoeuvres. The navigational marker "Flatholmen" is located on a small island close to the ship-lane in the centre of Figure 7.

Plan section	Manoeuvre parameter	Mean value
1	Course angle (rad)	0·32
	Speed (knots)	12·5
1 to 2	Transition condition	Angle (rad) to "Flatholmen" $<-1{\cdot}4$
2	Turn radius (m)	950
	Speed (knots)	10·2
2 to 3	Transition condition	Obtained course angle (rad) $>2{\cdot}27$
3	Course angle (rad)	2·26
	Speed (knots)	8·6

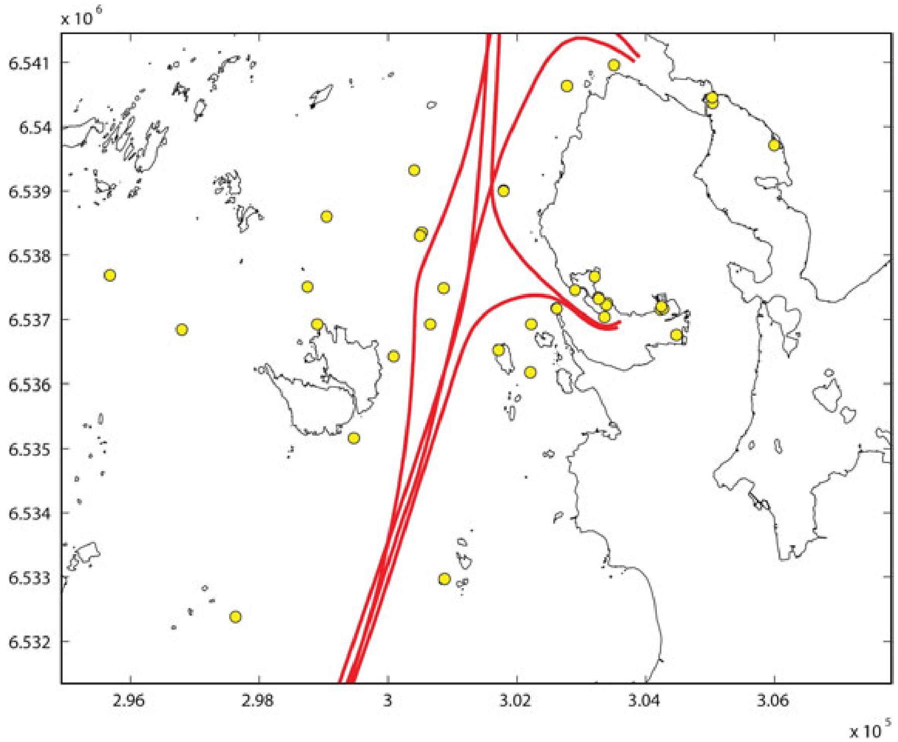


Figure 7. Sample area for simulations with navigational markings indicated as circles. The main ship traffic routes in the area shown with star markers where the traffic routes change from constant course to course change sections.

cumulative distribution function. Cross track spread values were converted to (x, y) pairs by placing them on a vector perpendicular to the mean course line. The initial course was computed by considering the angle between the initial point and subsequent sampled transition point. This procedure maintains both the mean course angle and evolution of the traffic spread as observed in the first section of the manoeuvre plan.

4.1.3. *Response time.* Response times are obtained from the statistical model by the same sampling procedure as the traffic spread. The response time is assumed

Table 3. Ship particulars for parameter sets available for the tanker model. Model No. 5 is a ULCC tanker and does not represent a ship that is encountered in the area. The ship is included in the table to summarize the complete set of parameters available, and has been used to check the autopilot procedure, but does not represent an operational case nor is it applied in simulations other than to check the ability of the autopilot formulation to control vessels.

Model No.	DWT	Lpp	B	T	Model Type
1	193 000 tons	304·8m	47·17m	18·46m	"Esso Bernica"
2	20 000 tons	146·5m	28·8m	8·9m	GEOSIM
3	100 000 tons	248m	38·6m	15·1m	GEOSIM
4	200 000 tons	305m	47·5m	18·5m	GEOSIM
5	500 000 tons	411m	64m	25m	GEOSIM
6	200 000 tons	240m	60m	18·5m	LB-SERIES
7	200 000 tons	274m	52·6m	18·5m	LB-SERIES
8	200 000 tons	305m	47·5m	18·5m	LB-SERIES
9	200 000 tons	332m	43·6	18·5m	LB-SERIES

invariant during simulations such that subsequent decisions share the same activation time. The median response time is parameterized from the vessel length and speed and is calculated by $T_{1/2} = D_{reponse}\ L_u$ with u being the ships speed, Lpp the length between main pp perpendiculars of the ship and $D_{response}$ a fraction specifying the number of ship-lengths required for action. This formula translates between the standard navigation measures of "*ship lengths*" to seconds which is used in the response model. The response time for the human operator, or the activation time of the functional relationship, is then derived as the time required travelling D number of ship-lengths at the present speed. A further modification of the median response time due to the impact of man machine interface, training and situation type is deferred due to the uncertainty already introduced through the calculation of the response time.

4.2. *Manoeuvre reproductions.* The first test of the formulation of the human element is the ability to execute manoeuvres and achieve the desired result. A dynamic model for a tanker with parameter sets for nine different vessel sizes from (Van Berlekom and Goddard, 1973) was used to test the manoeuvre performance of the autopilot formulation. The available parameter sets are summarized in Table 3. The model formulation from (Van Berlekom and Goddard, 1973) is favourable since it represents vessel dynamics as an IO-system with rudder angle and engine power is system inputs, an ideal interface to test the human element against. The area was modelled as a set of navigational markings with wind and current influencing the dynamics of the ship. The wind direction was from the north with a wind speed varying about $10m/s$ to represent harsh, but not severe, weather. The current was modelled as two flow fields, an outer field following the land contour with a typical current velocity form the area, and a smaller field in the narrow harbour entrance with a flow direction out of the harbour as seen with a rough indication of the manoeuvre plan in Figure 8.

The simulated manoeuvre plan is as follows:

- Follow a straight vessel course in the approach. Transition to next manoeuvre when the angle to "Flatholmen" is less than 80° starboard.
- Turn into the harbour with an ideal turn radius of $950m$. End turn when course of own ship is more than 130°.

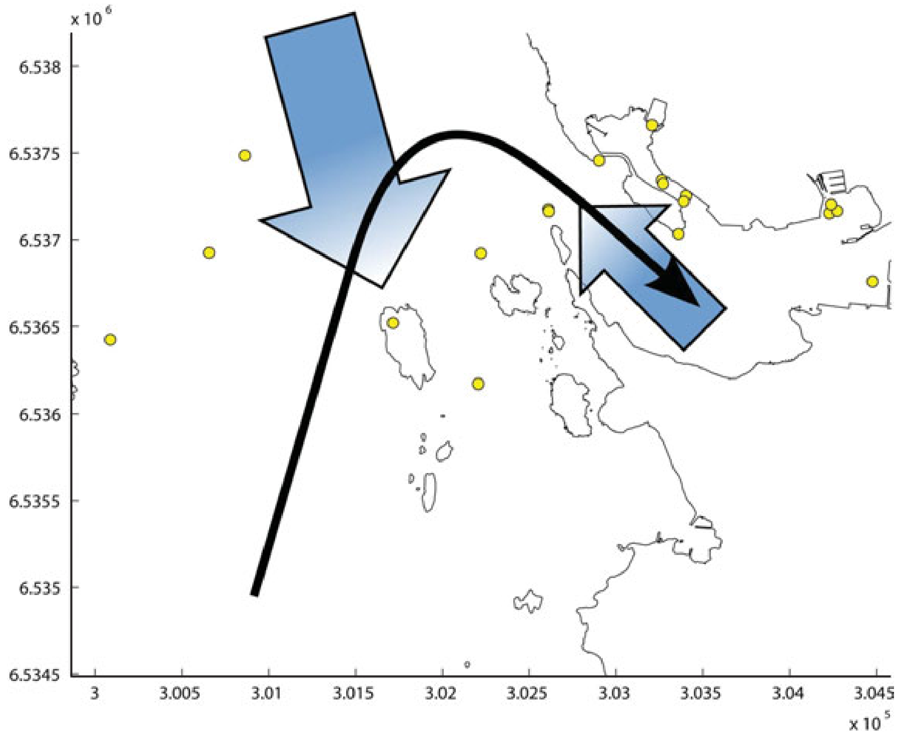


Figure 8. Manoeuvre plan and current directions in the area, current velocity is 0·5knots, strength and direction from meteorological observations of the area. Outflow current is added to increase manoeuvre complexity.

- Pass between the two navigational markings "Laksholmbåen" and "Tananger Lighthouse" at the harbour entrance.
- Continue toward harbour leading lights and minimize the apparent difference in course between them.

The simulated path of model No 4 in Table 3 is seen in Figure 9 with the imprint of the vessel superimposed. It is evident that the autopilot formulation is capable of manoeuvring the ship according to the manoeuvre plan in Table 2. Similar simulations for the all the parameter sets presented in Table 3 are seen in Figure 10.

The effect of ship dynamics and variation in activation times on the mean manoeuvre of Table 2 is seen in Figure 10. The results are obtained by navigating the sample manoeuvre plan with turn initiation points derived from the plan modified by the advance parameter of the corresponding dynamic model. From the results it is evident that the dynamic of the ship contributes to the shape of the traffic, but the magnitude of this contribution is smaller than the possible variation in traffic resulting from a variation in activation time as prescribed by the SRK framework seen in Figures 11. The reproductions of traffic patterns cannot rely entirely on mean manoeuvre predictions as traffic that enters the area already exhibit a dispersed pattern. The influence of the initial condition on the traffic spread is seen in Figure 12 where the starting point of the simulation together with the course is calculated by drawing samples from the distribution estimated from the dispersed arrival pattern obtained form analysis of AIS data.

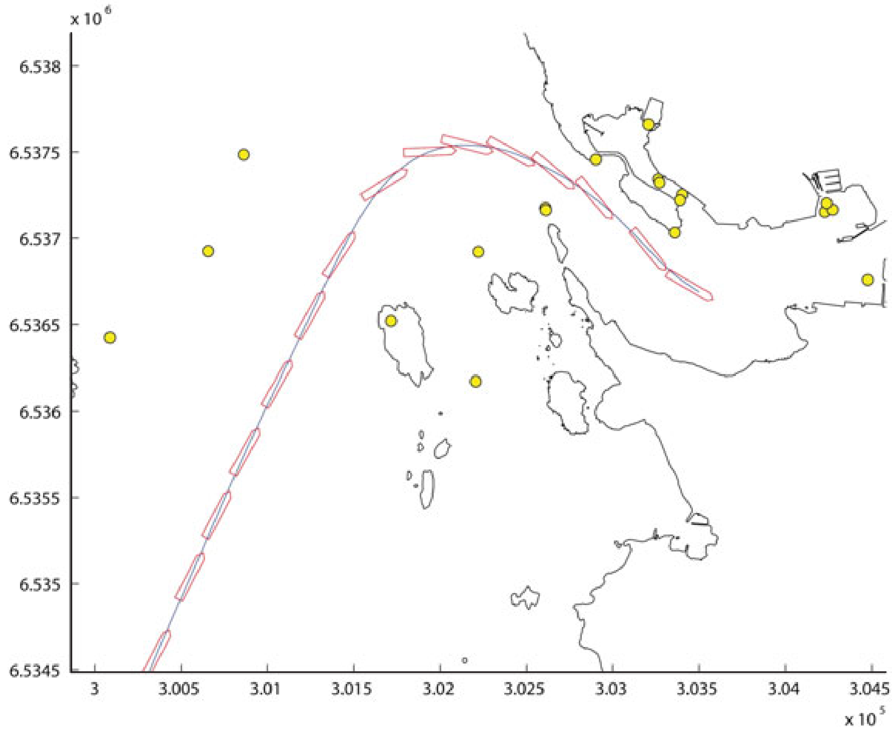


Figure 9. Ship position and orientation during mean manoeuvre with 200 000 DWT tanker model No. 4, ship imprint is plotted with 60s interval. The true heading of the ship is not equal to heading from the centre of gravity trace in the approach due to influence from current.

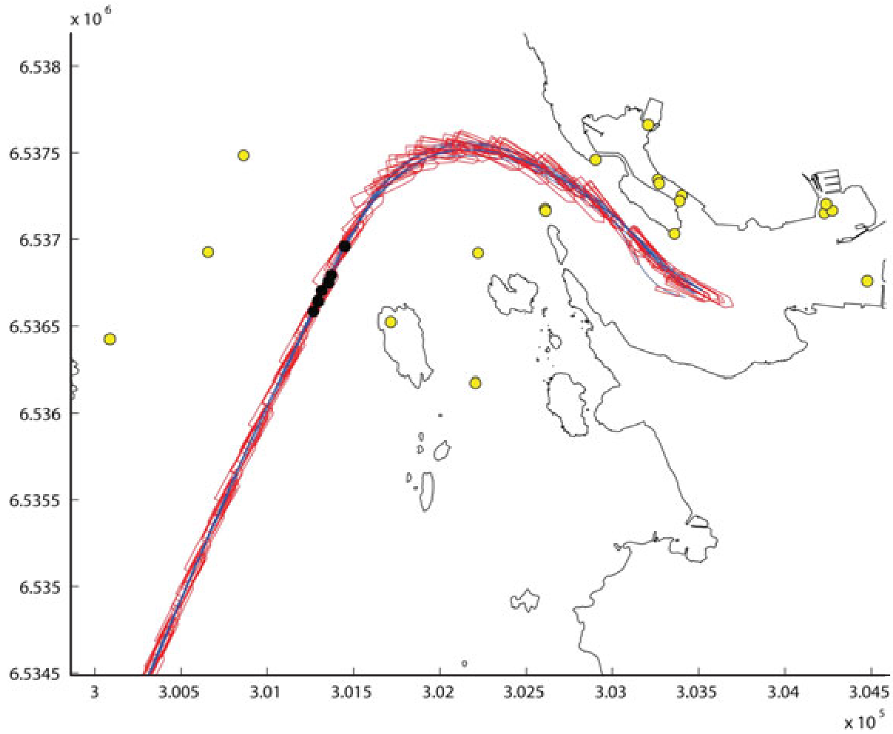
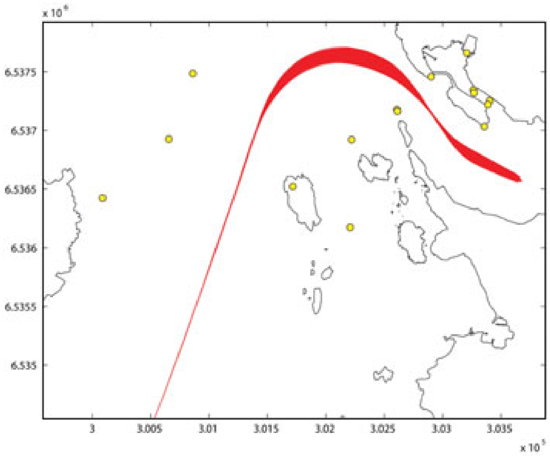
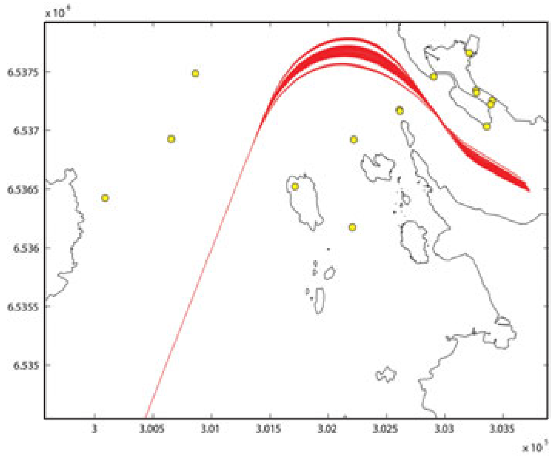


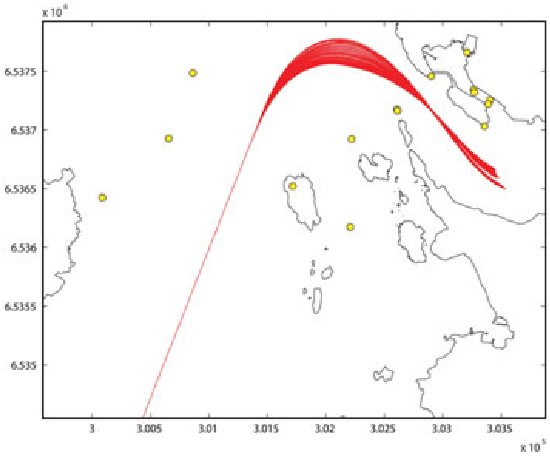
Figure 10. Reproduction of the mean manoeuvre plan with nine different ship dynamics. Operator performance is assumed to be on the "skill" level with response time derived from Presponse, skill = 0·1. The figure shows the track of the ships centre of gravity with ship imprints at approximately 60sec intervals. The wheel over point is shown as black dots on the track-line.



(a) Skill processing response



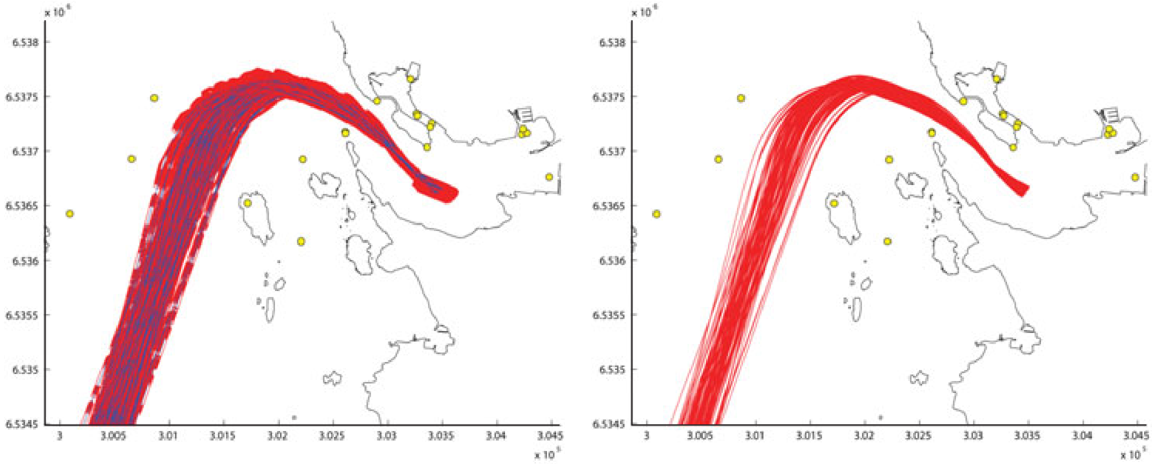
(b) Rule processing response



(c) Knowledge processing response

Figure 11. Mean manoeuvre simulation of model No. 4 (200 000 DWT) with varying response times from skill-rule-knowledge processing. The response time was derived by selecting a probability level $P_{response}$, $i = x$, where $i \in \{skill, rule, knowledge\}$. The actual response time was calculated form the response curves of (Hannaman and Worledge, 1988) with $x \in [0, 1)$, values of x were evenly spaced in the interval. The expected spread from variation of the response time is seen consistently increasing with the processing type.

5. DISCUSSION. It is crucial that the formulation of the navigational plan and the implementation of switching between individual autopilots according to the manoeuvre strategies are capable of successfully piloting the vessel models into the harbour. This property is evident in Figures 9 to 12, which show the system negotiating the harbour entrance by geometric observations of the surrounding navigational markers. The traffic patterns of the SRK framework all converge on a specific point in the harbour approach. This is due to the introduction of a rule to pass between the navigational markers at the harbour entrance. The natural spread in traffic is captured by the simulation when the variability in performance is introduced by the SRK based response functions which result in a fan-like evolution of the traffic as the response time is varied along a continuous scale. However, the spread in traffic is greatly influenced by the entry point into the area; the entry point represents the past variation in performance and origin of the vessels. The



(a) Traffic with ship imprints (b) Traffic with traces of ships centre of gravity

Figure 12. Traffic reproduction with model No. 4 (200 000 DWT) with varying initial conditions and operator response. Operator performance is assumed to be on the "skill" level with response time derived from $P_{response}$, skill = 0·1.

entry point and orientation must be combined with the SRK response function to fully capture the behaviour of the traffic in the area. From Figure 12 it is evident that this combination captures the observed traffic pattern in Figure 7, but lacks traffic in areas in close proximity to islands and protruding landmasses. This is believed to be due to the inability of the navigation model to capture opportunistic manoeuvring patterns of highly manoeuvrable vessels that can follow the coastline without a prescribed or intended shape of manoeuvring.

It might be possible to capture this traffic component by application of a separate navigational plan, but the single navigational plan identified from AIS by the method established in (Aarsæther and Moan, 2009) cannot be used to support an additional manoeuvre plan of this form. Another aspect of the simulation model that needs to be scrutinized is the representation of the human element. The SRK framework with response curves necessitates a reduction of the complex human element to a simple time-response component. This effectively eliminates any possibility of attributing the behaviour of the vessel past the response time. The representation of the human element appears in the causal chain as a singularity where the complex behaviour of the human element is distilled down to a single number. The man-machine interaction that in reality is taking place can be envisioned as a dynamic system with multiple actors and interactions, but the whole process is reduced to a single property in the time to respond. This reduction is irreversible and the additional information that could have been represented in the model of the human element is superfluous since the reduction to a single number renders the actual behaviours indistinguishable from each other. The simulated environment on the reverse side of the singularity only experiences the effects of the time-response system. This is analogous to the placement of the human operator model on the functional system description level where we only have enough information to reproduce the system response, not model it or derive the relationships between the components of the system. This implies that while the simulated model can represent the variation of human performance, via the time-response component, it cannot be used to make any predictions about how or why the response time is as experienced. This singularity is similar to the effect of integrating human factors analysis into classical fault tree based risk analysis techniques where the human reliability analysis is used to deliver a probability of success or failure that is subsequently treated as any other as a system component.

6. CONCLUSION.

The autonomous system model with a simplified human operator model has been shown to be capable of navigating from a plan based on navigational markers as well as capable of reproducing observed manoeuvre patterns. The structure of the autopilot with a separation of planning, decision and execution was inspired by research in human performance, but based on the old stimulus-response operator models due to the lack of time-domain applicable developments in recent years. This relationship is beneficial because it provides an underlying model for the implementation but also the application of simulation theory highlights the deficiencies of operator modelling. The deficiencies of operator models are in the realm of quantitative models; recent human operator models has focused on robust quantitative models of human behaviour, whereas the quantification of effects are of uttermost importance in simulation studies.

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A.2 Background paper

Combined Maneuvering Analysis, AIS and Full-Mission Simulation

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Combined Maneuvering Analysis, AIS and Full-Mission Simulation

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ABSTRACT: This paper deals with a method for identifying the main parameters of a maneuver using both real-time full mission simulators and positioning data obtained from the Automatic Identification System of the same area. The effort required for experiments in real time maneuvering is naturally larger than the effort required to collect already available data. Analysis of both data sources is presented. We show how the curvature of the ships track can be related to the wheel-over point and further used to estimate the main parameters of a course-changing maneuver. The southern approach to the Risavika harbor in the southwest of Norway is used as a demonstration. The approach angle and turning circle diameter was accurately identified in both AIS and simulator data, but significant navigational markings was only quantifiable in simulator data.

1 INTRODUCTION

To investigate the effect on navigation decisions and external effects on ship maneuvering it is convenient to test these scenarios in a simulator with controlled conditions and good opportunities for data collection. If such simulations are to represent the real world it is important that the processes that are simulated are similar to their real world counterparts. In traditional fully automated maneuvering simulations (Hutchinson, 2003, Merrick, 2003), a regular control-theoretic guidance and autopilot combination is often used to represent the maneuvering decisions on the bridge of the ship. This control theoretic construct is not well suited to represent the decisions on the bridge, as it does not follow the same guiding rules as a human would. The first step to replace this control theoretic construct is to identify the proper maneuvering processes and then to quantify their main parameters. These main parameters can later be used as input to a numerical navigator for fully automatic maneuvering simulation. Quantification of the main features and parameters can be made from expert opinion and simulator studies with human operators. Simulator studies are a costly and time consuming process, but offers the best accuracy and provides control of the environment in which the maneuver is executed. Simulator studies can also be augmented by real world data whenever possible, with simulator studies providing the entry point into analysis of coarser real world data.

Data from the Automatic Identification System (AIS) has a potential to reveal the preferred navigational patterns and maneuver parameters in use in a specific area. The AIS system is implemented by all IMO member states as per requirement of SOLAS. The system represents an opportunity to study the traffic and navigational patterns in costal areas. Data available from AIS introduced in recent years has not been used for this purpose.

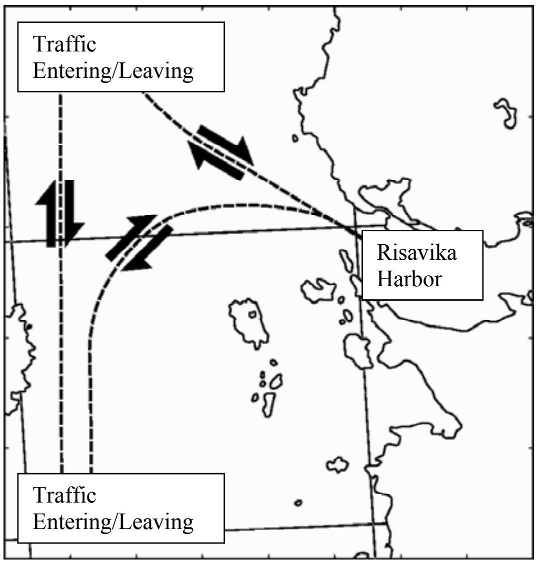

Fig. 1. Risavika With Main Traffic Concentration

In this paper we will show how the main parameters of maneuvering can be quantified by use of simulator trials and AIS data. We will focus on the area around the Risavika harbor in the southwest of Norway. An overview of the area and the main traffic routes is seen in Figure 1. The routes of traffic shown are extracted from AIS data from the area.

1.1 *Representation of maneuvering*

Maneuvering of a ship in transit can be represented as a combination of course keeping and course changing maneuvers stringed together to form a complete plan for the voyage. This representation is described in (Lüzhöft, 2006) where it is presented as the standard planning procedure for pilots and shipmaster operating in the costal areas around Stockholm in Sweden. The voyage plan is in the form of straight sections with the heading for both passage directions noted with turning diameters for each turn. In addition the significant landmarks and navigation aids used to determine when and where to transit between these maneuvers are noted. The maneuvers of the vessel is joined together at points where the wheel of the vessel is either used to initiate a turn (wheel-over-point) or the point where action is taken to exit the circular turn path (pull-out-point). The approach to Risavika harbor is modeled as a section with constant course followed by a Rate-of-turn maneuver to change the vessels course to a more beneficial course for entry into the harbor.

1.1.1 *Course keeping*

Course keeping is the simplest of maneuvers and is the task of keeping the vessel on a straight course. The only variability one expects is the individual error tolerances in deviation from desired course or the variability in entry of autopilot targets. The main parameter of this maneuver is the desired course.

1.1.2 *The rate-of-turn maneuver*

The rate of turn maneuver is marine craftsmanship and is based on simple rules of thumb calculations of an object speed and the curvature of the path it follows. An object will travel on a circle of diameter *D* if the ratio of the speed and rate of turn is constant; the constant determined by the circle diameter is a defining parameter of the maneuver. The rate-of-turn of the vessel is reported as degrees per minute on the bridge of the vessel. The time in minutes for a vessel with speed *V* m/s to complete a turn of 360° on a radius of *r* m is

$$t = \frac{2 \cdot \pi \cdot r}{V} 60 \tag{1}$$

To get the rate of turn in ° per second needed to stay on the circle of radius *r* we divide 360° with time from Equation (1).

$$ROT = \frac{360°}{\frac{2 \cdot r \cdot \pi \cdot 60}{V}} = \frac{3° \cdot V}{r \cdot \pi} \approx \frac{V}{r} \tag{2}$$

The final simplification is to transfer the expression into an easy to remember rule of thumb. This simple rule is the foundation for the rate-of-turn maneuver where the master of the vessel actively will use the controls to keep the relationship between the vessel speed and rate-of-turn constant. The constant determines the radius of the turning circle. The turning circle radius is then the defining characteristic of the rate-of-turn maneuver. In a nautical setting the rule is applied with knots as speed and nautical miles as measure for the radius. With a given turning radius of 0.5 nautical miles, this relationship between rate of turn and speed in knots easily gives the required rate-of-turn for this maneuver.

$$ROT = \frac{V}{0.5} = 2 \cdot V \tag{3}$$

1.2 *Quantification of parameters*

From the AIS data and simulator trials the following maneuvering characteristics were identified in the northbound approach to Risavika:

- Approach course angle
- Number of turning maneuvers used
- Wheel-over-point position
- Pull-out-point position
- Mean and max turning circle radius for each turning maneuver

The Rate-of-turn maneuver used in the simulator study has characteristics, which we also can calculate from the data available from AIS. This will be done in turn to show the accuracy of these calculations. The radius of the turning circle used in the maneuver is identifiable from the rate-of-turn vs. speed ratio maintained by the vessel during the maneuver.

The curvature of the track line can be used to extract the number of turning maneuvers used on a section of the passage.

From the charts of the area and the simulator environment we have the location of the significant navigational lights in the area. The positions of these lights are used together with the wheel-over and pull-out points to try to determine the most probable navigational light used. The position of the navigational lights in the simulator area was used both in the simulator trials and in the analysis of the AIS data.

2 SIMULATOR TRIALS

Full mission simulator data was recorded from training exercises at the Ship Maneuvering Simulator Centre (SMSC) in Trondheim, Norway. Simulator trials were used to determine a benchmark maneuver and used with the greater fidelity of the synthetic environment to analyze the time series of available variables. Simulations where carried out with human operators on the bridge simulators piloting the vessel into Risavika harbor. The simulator centre has three full mission simulators in operation and by introducing an automatic logging application on the simulator network the communication from each simulator was intercepted. The start of logging was triggered by the start of the exercise for the Risavika maneuver. Data was written to disk and made both the simulated vessel state as well as the control inputs for rudder and engines available as time series for offline analysis. Data was sampled at 1 sec intervals to limit file size.

2.1.1 *Trial maneuver*

The trial maneuver selected for study was a maneuver to enter the harbor in Risavika from the south starting at a course of 0° N. The starting position for the ship has no obstructions on the initial heading, and will with the initial speed in a relatively short amount of time be in a position to initiate the turning maneuver into the harbor. The turning maneuver into the harbor is predefined. The bridge crews were instructed to change the ship's course using a rate of turn maneuver with a radius of 0.5 nautical miles until they were on a course suitable for the final approach. By inspecting the rudder time series in the simulator trials the wheel-over-point for the transition between the first course keeping section and the rate-of-turn maneuver was identified. This point for each dataset allowed calculation of the heading at the time of maneuver transition, and the angle between the vessels and all the visible navigation lights in the simulated area. The same procedure was used to identify the pull-put-point, completing information about the maneuver.

2.1.2 *Results*

In total 44 maneuvers were recorded from SMSC exercises with a variety or bridge crews. Some exercises were discarded due to approach path. The discarded exercises followed a radically different path with fundamentally different features than the typical maneuvers, 36 cases remained in the end. Maneuver transition points and track curvature was extracted form this data. The mean and max value of the relationship between rate-of-turn and the speed during the rate-of-turn maneuver is seen in Figure 2.

Figure 2 shows a median value of the mean rate-of-turn/speed relationship of *1.75*. This translates to a turning circle radius of *0.571* nautical miles. If we account for the introduction of *3/3.14 = 1* in the rule-of-thumb simplification of the formula, the theoretical turning circle has a radius ≈ *0.54* nautical miles. The deviation then becomes only *0.03* nautical miles and is in good agreement with the theoretical value. Both mean and max values shows skewed data. The mean rate-of-turn/speed relationship packed tight around the median. The results showed very good agreement with the ideal turning circle radius one should expect from the briefing. Some of the deviations are from the exercises following a slightly different path into the harbor.

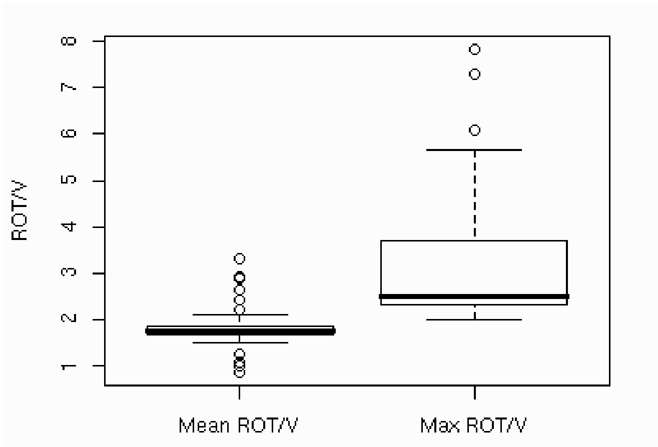

Fig. 2. Distribution of rate-of-turn/speed from simulator trials

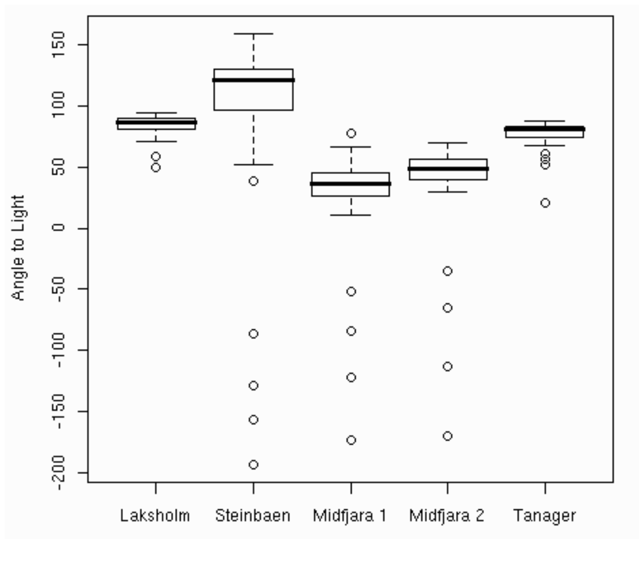

Fig. 3. Angle from vessel to navigational lights in simulator trials at the wheel-over-point

The results from the calculation of the angle between the wheel-over-point and the visible lights in the simulator were plotted as a boxplot to determine correlation. The results are seen in Figure 3, where the angle to the first landmark seems to be very consistent across trials and at an angle of 90° it is preferable since it is indifferent to cross track deviations (the last landmark is in close proximity, and shows a very similar distribution). If the first landmark is taken as the significant maneuvering landmark used, then we can find a statistical description of the variability of the wheel-over-point in relation to the angle to the landmark. We see a skewed distribution around a median of about 90° for the first landmark, with a few outlier cases, again from a different approach path.

Another result from the simulator experiments was the relation between the Wheel-over-point, Pull-out-point and the local extreme values of the track curvature. The wheel-over point was always located near a local minimum while the pull-out point was located near a local maximum. An example time series is seen in Fig. 4 where the relevant points are indicated. The nonzero curvature for zero rudder angles shows the tendency of single-screw ships to turn at zero rudder angles due to propeller inertia and asymmetric flow around the stern

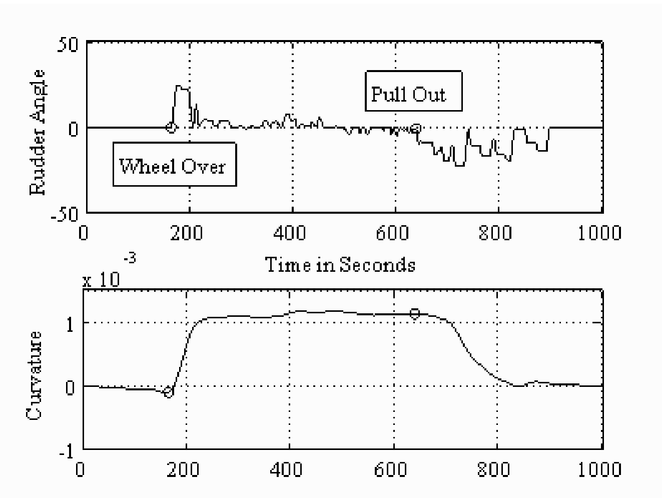

Fig. 4. Rudder angle and curvature in relation to wheel-over and pull-out points

In the simulator studies the difference in time between the Wheel-over-point and the local minimum was computed and is shown in Fig. 5. This proximity can be used to make a qualified guess about the location of these points based on rate-of-turn and speed data. The local extreme value behavior will be used later to find good candidates for wheel-over and pull-out points in the AIS data for the same area.

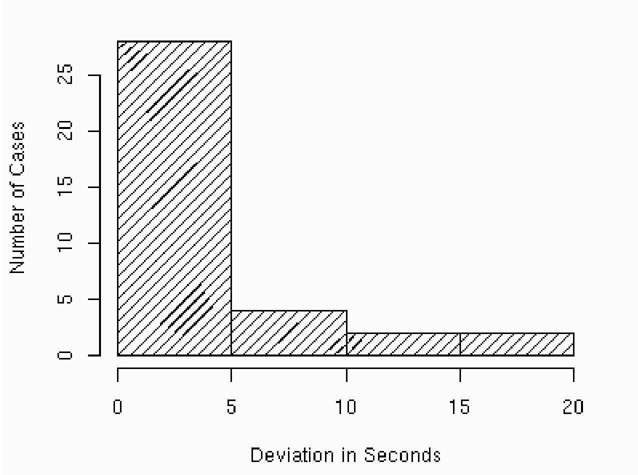

Fig. 5. Wheel-over-point deviation from local extreme value of the track line curvature

3 AIS DATA ANALYSIS

The Norwegian Costal Administration provided AIS data in form of position reports for April, May and June 2006 for the presented area. The position reports where then restricted to the immediate area around Risavika before it was grouped according to each ships unique MMSI number (IMO, 1974). Requiring the track line to start to the south and end in the harbor was used to restrict the AIS data further. The data for each MMSI number was then further sorted by time and grouped in space to form datasets of track lines continuous in these dimensions. This procedure was necessary due to the presence of misconfigured AIS transponders making identification solely based on MMSI number difficult. The AIS data received contained time, position, speed over ground, rate of turn and course over ground. The sample rate of the AIS data depends on the ships speed and state of the vessel and will during transit and turning maneuvers for moderate speed be in the area of *0.3 – 0.5* Hz (IMO, 1974).

The AIS data does not contain information that makes it possible to pinpoint the transitions between the different maneuvers, such as the instantaneous position of the rudder. We can however find features from the maneuvering techniques used in the data in form of the speed, rate-of-turn and position in the AIS data with an accuracy of about 5 seconds as presented in Fig. 4 and Fig. 5. The AIS data does not contain rate-of-turn information for all vessels, but calculation of the curvature of the track line of the vessel will accurately identify the value of the speed/rate-of-turn relationship. The ratio between the vessels rate-of-turn and the speed relationship corresponds to the curvature of the ship track. Calculation of the curvature will work regardless of the absence of rate-of-turn information in the signal. The total number of AIS track lines was 429, which was further subdivided into 308 single turn maneuvers, 107 two turn maneuvers and 14 maneuvers with 3 or more turns which were discarded due to accuracy of the procedure and implied poor accuracy in the position reports.

3.1.1 *Calculating curvature from position data*

The curvature κ of the ships track can be calculated from the position and time data. This can done by filtering the position data to remove noise and then use a numerical expression for the curvature calculated by solving the equation for a circle passing through the three consecutive points. κ can also be directly from the time domain signals for the position $x=x(t)$ and $y=y(t)$. The curvature of these two signals in Cartesian coordinates with ϕ as the tangential angle of the signal.

$$\kappa = \frac{d\phi}{ds} = \frac{d\phi/dt}{ds/dt} \tag{4}$$

$$\kappa = \frac{d\phi/dt}{\sqrt{(dx/dt)^2 + (dy/dt)^2}} = \frac{d\phi/dt}{\sqrt{(\dot{x})^2 + (\dot{y})^2}} \tag{5}$$

The need for $d\phi/dt$ can be eliminated by the following identity

$$\tan\phi = \frac{dy}{dx} = \frac{dy/dt}{dx/dt} \tag{6}$$

$$\frac{d\phi}{dt} = \frac{1}{\sec^2\phi}\frac{d}{dt}(\tan\phi) \tag{7}$$

$$\frac{d\phi}{dt} = \frac{1}{1+\tan^2\phi}\frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\dot{x}^2} \tag{8}$$

Equation (8) substituted into Equation (5) gives the final expression for the curvature

$$\kappa = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{(\dot{x}^2 + \dot{y}^2)^{3/2}} \tag{9}$$

This expression for κ relies on the derivative and double derivative of the vessel track line positions. Numerical calculation of these derivatives from noisy position data is inherently error prone. Instead of calculating the derivatives numerically, the derivatives are evaluated by fitting polynomials to the $x(t)$ and $y(t)$ signals. It is impossible to find a general polynomial to describe the complete track with sufficient accuracy for the entire ship track. To calculate the curvature at a specific track sample, a 5^{th} order polynomial is fitted at a section spanning 20 samples both forward and backward in time. This provides both a theoretical form for the evaluation of the derivatives and suppresses the noise in the positioning data. The derivatives and double derivatives can then easily be evaluated from the corresponding formulas for polynomials. The polynomial fit was computed using MATLAB's 'polyfit' function using both centering and scaling to improve the numerical properties of the fitting procedure.

3.1.2 *Detection of turning maneuvers*

Detection of turning maneuvers was done by discretizing the number range for the curvature into regions of size *1e-4*. The curvature signal was then compared to this interval forming an array of *0* and *1* values. The array represents the image of the area between the x-axis and the curvature signal. This representation made it easy to determine where the curvature crossed certain numerical values, and how many crossings it did of a particular value. The curvature level used to detect significant changes in track curvature was *3e-4*; the number of crossings over this value was easily extracted from the line of the kappa image array corresponding to this value. The number of up-crossings over this value was an initial estimate of the number of turns in the maneuver. The area beneath each turn was compared and if the area during one turn of a two-turn maneuver was less than 10% of the area of the other turn, the maneuver was reclassified as a one-turn maneuver. After the turning maneuvers were identified the Wheel-over and pull out point where assigned to the local extreme values.

3.2 *Results*

The results from the AIS data processing showed a deviation in the preferred route into the harbor for the southern approaches compared to the simulator experiments. The difference concerns the approach angle towards the harbor, making the turn into the harbor less severe in reality than in the simulator. The AIS data further showed that the traffic entering the harbor was divided into one and two turn approaches. The one turn approach still followed the same basic principle as the simulator experiments, while the two turns approach used an additional course-changing maneuver before the final turn into the harbor. The two-turn approach followed a separate pattern with a course change roughly the same place as the one turn maneuver but with a final sharp turns used to enter the harbor. Only data for a single turn maneuver is used to calculate the approach angle, curvature, wheel-over and pull out points.

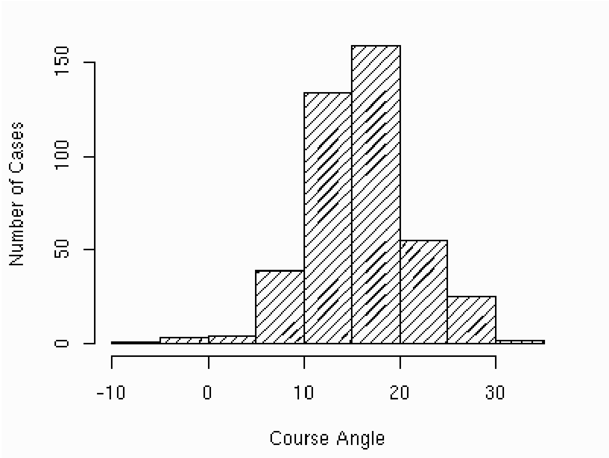

Fig. 6. Course angle at the wheel-over-point

The curvature of the track line was calculated as described in Section 3.1.1 and is shown in Fig. 7. The mean and max curvature is calculated using values between the wheel-over and pull-out point identified in the manner described in Section 3.1.2. The results are similar to those of the simulator study but with more variation and a larger discrepancy between the mean and max curvature. The median of the mean curvature is *0.00101* corresponding to *990m ≈ 0.535* nautical miles. This result fits nicely with the numerical values for the turning circle diameter estimated from the simulator trials. The curvature distribution from AIS is less skewed and follows a more normal distributed form. Outlier cases are fewer as shown in Fig. 7, but the maximum curvature shows a far greater range.

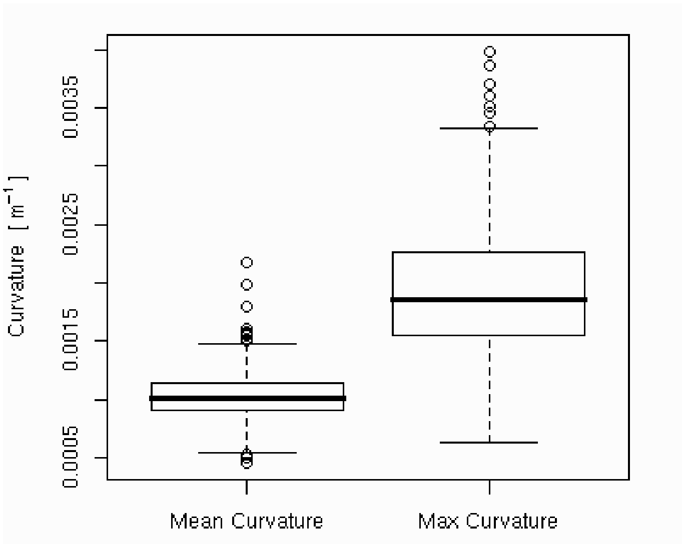

Fig. 7. Curvature of AIS Track Lines During Turn

The wheel-over and pull-out point for the AIS data was harder to quantify, and only a qualitative conclusion could be drawn from the data. No clear candidate as in the case of the simulator trial emerged.

4 DISCUSSION

The approach angle, number of turns and turning circle diameter was well estimated with a good accuracy in comparison with the values found in the simulator trials. The relatively small number of simulator trials highlights a drawback: the limited amount of time and resources to study a maneuver. However a more intense simulation program can mitigate this effect.

The position of the wheel-over and pull-out point is harder to relate to the navigational lights in the area. This may be because of the inherent error in estimating these points from the curvature or due to the numerical effects on the calculation due to the proximity of the navigational lights to the track line, exaggerating any errors in the angle estimate. Another cause for the difficulty in identifying a pattern in the wheel-over and pull-out points in the AIS data is the possibility that its high dependence of vessel dynamics makes it a poor candidate for analysis across a wide selection of vessels. The points where the track line curvature exceeded 1e-4 were more clustered around a specific point. This effect is possible with a large selection of ships with different dynamic responses all aiming for the same turning circle starting at the same point, a pattern we have seen in the AIS data. This effect can be further investigated using static ship data available from the ITU's Maritime mobile Access and Retrieval System database linked with ship statistics for dynamic response.

The turning circle diameter used and the number of turns used was more accurately identified in both the simulation trials and the AIS data from the same area. Ships entering Risavika use a turning circle diameter of 0.5 nautical miles for one course change approaches to the harbor. The main difference from the simulator trials here is the approach angle which was 15° in service compared to 0° in the simulator studies. Ships using a 0° approach angle used navigational light 1, "Laksholm" initiating the turn at 90° angle. This pattern was also visible in AIS where a very limited number of vessels used the 0° approach.

5 CONCLUSION

It has been shown that analysis of the ship track line can be used to estimate the parameters of standard maneuvers. This can be useful either in conjunction with simulator studies or by itself. The parameters of the rate-of-turn maneuver extracted from the combination of simulator and AIS data can be used later as input to a numerical navigator to mimic the behavior of the real navigator. AIS present itself as an easily available source of information about the desired maneuvering patterns in a specific area. More importantly the parameters of the maneuvers are quantifiable from this data. The navigational aids used are best identified using full-mission simulation or expert opinion.

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UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
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UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
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UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension

		Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
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MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
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MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
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75		Assessment of Submarine Pipelines. (Dr.Ing. Thesis)
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MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
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		Members. (Dr.Ing. Thesis)
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MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
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MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
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		Thesis)
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