Validation of ship intention model for maritime collision avoidance control using historical AIS data

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***Abstract*— This article tests the method for inferring and modeling ship intentions presented in [1] on real ship encounters gathered through the automatic identification system (AIS) that all larger ships are required to use. Empirical distributions on how early ships tend to perform avoidance maneuvers and how close they tend to come are evaluated. These are used by the intention model to identify when a ship's behavior is outside normal behavior. Running the intention model on the historical ship encounters demonstrates that the intention model is able to correctly infer the intentions of ships in real collision encounters. The model is able to distinguish between different types of incompliant behavior such as a ship not giving way when it should, the wrong ship giving way, or a ship giving way in the wrong direction. Some improvement potentials are identified, mainly with respect to understanding when the situation starts.**

I. INTRODUCTION

The International Regulations for Preventing Collisions at Sea (COLREGs) [2] outlines rules on how to act to avoid collision at sea. These rules are intentionally written quite vague, and they rely in large parts on good seamanship to define when to act and how large actions that are needed. This makes it harder for autonomous ships both when it comes to deciding how to act and when it comes to understanding how the other ships are acting. Understanding the intentions of other ships is crucial as there can be different interpretations of the current situation making it unclear which ship should act [3], [4], as there might be local rules or customs that go contrary to COLREGs [5], [6], and as some ships might not know or choose to follow the rules.

In [7] three classes of obstacle models used in collision avoidance algorithms are presented. The first, called physics-based models, assume that the ship will keep a constant course and speed, where control inputs from the captain can be considered as noise. The second, called maneuver-based models, considers the intentions of the ships either with respect to avoiding collision by considering COLREGs or by considering historic data on traffic patterns. The last type is called interaction aware models and considers cases where there is communication between the ships. This class will not be considered further in this article as communication not always is available or reliable, especially when considering an autonomous ship operating between manually controlled ships.

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Of the collision avoidance algorithms that use a physics-based model, the stand-on obligations of the own ship are either not considered, as reviewed in [8], considered by weighting the stand-on obligations against a collision risk measure that increases as the ships approach [9], or by not considering obstacle ships with give-way obligations that are sufficiently far away [10]. A method for identifying when a stand-on ship should give way is given in [8].

The maneuver-based models which identify traffic patterns are useful for predicting the long-term trajectory of other ships [11], but must be combined with a collision-avoidance-based model as ships will divert from the traffic patterns to avoid collision. In [12] a collision avoidance algorithm is presented that considers multiple future trajectories of obstacle ships but does not consider how the trajectory probabilities should be evaluated. Only [1], [8] have presented methods for inferring and modeling the intentions of ships with respect to COLREGs. The algorithm in [12] is combined with the intention inference model in [1] to produce an intention-aware collision avoidance algorithm in [13].

The intention inference method presented in [1] evaluates the probability of an obstacle ship having different intentions. These can either be used to evaluate the probability of the obstacle ships following different trajectories as done in [13] or could potentially be used to evaluate when the own-ship should disregard its different obligations, such as deciding when algorithms like [10] should start considering give-way ships. In [1] it is demonstrated how the intention model is able to identify and distinguish between different types of compliant and incompliant behavior, how it is able to identify situations prone to cause misunderstandings, and how the model can be adapted to local conditions.

In [1] the model is only tested on simulated cases where the goal is to illustrate and verify how the model works. In this article, the intention model is tested on historical encounter cases gathered with the automatic identification system (AIS). Furthermore, the example distributions used by the intention model in [1] are here replaced with distributions extracted from the historical AIS cases. The contribution of this article is to test how the intention model performs on real ship encounters with real distributions, thereby validating the model and identifying potentials for improvement.

The rest of this article is structured as follows. First, a short introduction to COLREGs is given in Section II. Then an overview of the AIS data set is given in Section III. Section IV outlines the intention model and the distributions used by the model are presented in Section V. The results

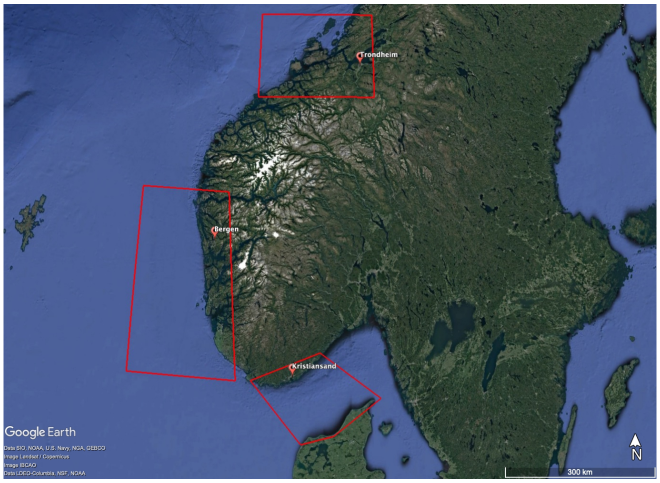

Fig. 1: Areas outside the Norwegian coast where AIS data is collected [14].

of applying the model to historical AIS cases are given in Section VI and discussed in Section VII, before a conclusion is given in Section VIII.

II. COLREGS

The most relevant rules in COLREGs are as follows: Rule 7 specifies how a ship should identify if there is a risk of collision. Rule 8 specified that actions to avoid collision shall be readily apparent, be made in ample time, and result in the ships passing at a safe distance. Rule 13 considers overtaking and specifies that the overtaking ship shall give way for the one being overtaken. Rule 14 considers head-on scenarios where both ships shall take a starboard action such that they pass port-to-port if there is a risk of collision. Rule 15 considers crossing and specifies that the one with the other on its starboard side shall give way behind the other ship, if possible. Rule 16 specifies that give-way vessels shall take early and substantial actions. While rule 17 specifies that a vessel not giving way shall stand on by keeping its course and speed. It also specifies that if a stand-on vessel is forced to give way in a crossing situation then it shall avoid doing so toward port when it has a ship on its port side.

III. AIS DATA SET

This article uses a AIS data set provided by the Norwegian Coastal Administration (Kystverket) collected from the three different regions outside the coast of Norway shown in 1. The data is gathered during different periods between 2018 and 2021. The most important part of the AIS message for this article is the time stamp, the unique identifier of each ship, their position, course, and speed over ground. Note that, generally, only larger ships are required to have AIS transponders [15]. This means that there might be ships present but not in the data set, which affected the behavior of the logged ships.

This data set has been previously analyzed by multiple master theses [16]–[18] and doctoral thesis [14] at NTNU. From these works a refined data set is produced consisting of 28421 encounter situations, of which 1206 are manually classified to be actual collision encounters where the ships act in accordance with COLREGs. The data available for the research presented in this article is:

- One file for each encounter case, consisting of the timestamps, id, position, speed, and course of all ships in the encounters. The data has a frequency of one message per 60 seconds.
- A list over all encounter cases and automatically extracted parameters.

IV. MODEL

A. Overview of the model

The intention model presented in [1] is made using the dynamic counterpart of Bayesian belief network (BBN), called dynamic Bayesian network (DBN). These are directed acyclic graphs which can be used for probabilistic inference [19]. The GeNie software [20] is used to build the DBN, while the SMILE engine is used for online inference [21].

Figure 2 shows the topography of the intention model. The intention nodes, shown in orange, are stochastic variables where the state is unknown. A prior distribution is provided to these nodes, see Section V, which can then be gradually updated when observations are made. The measurement nodes, shown in green, represent observable quantities. These nodes are not stochastic as their state is known. Finally, we have the model variables, shown in blue. These represent how the intentions and measurements relate to each other. There are two main types of intention nodes. The first represents uncertainty in the definition of different vague terms in COLREGs, such as what “ample time” and what “safe distance” is. These are modeled as continuous random variables. The second type represents ways the ship can violate the rules specified by COLREGs. These are modeled as binary or discrete random variables.

The intention model is updated by inserting an observation as evidence on the measurement nodes. The top node, “measurements compatible with intentions”, evaluates the likelihood of making this observation given our beliefs regarding the intentions. The intention beliefs are updated by setting the top node to be in the state “true”. A new time step is introduced for each measurement. The intentions are assumed to not change throughout the encounter and are therefore modeled as time-independent nodes. Note that even though the underlying intentions are assumed constant, our belief regarding what the intentions are will develop as new observations are made.

Some of the most important intention and model nodes are as follows:

- Ample time: According to COLREGs rule 8 avoidance actions shall be made in ample time. Before this time instant, the ship is allowed to keep its course and speed. What constitutes ample time is uncertain and may depend on several factors.
- Safe distance: According to COLREGs rule 8 avoidance actions shall result in the ships passing at a safe

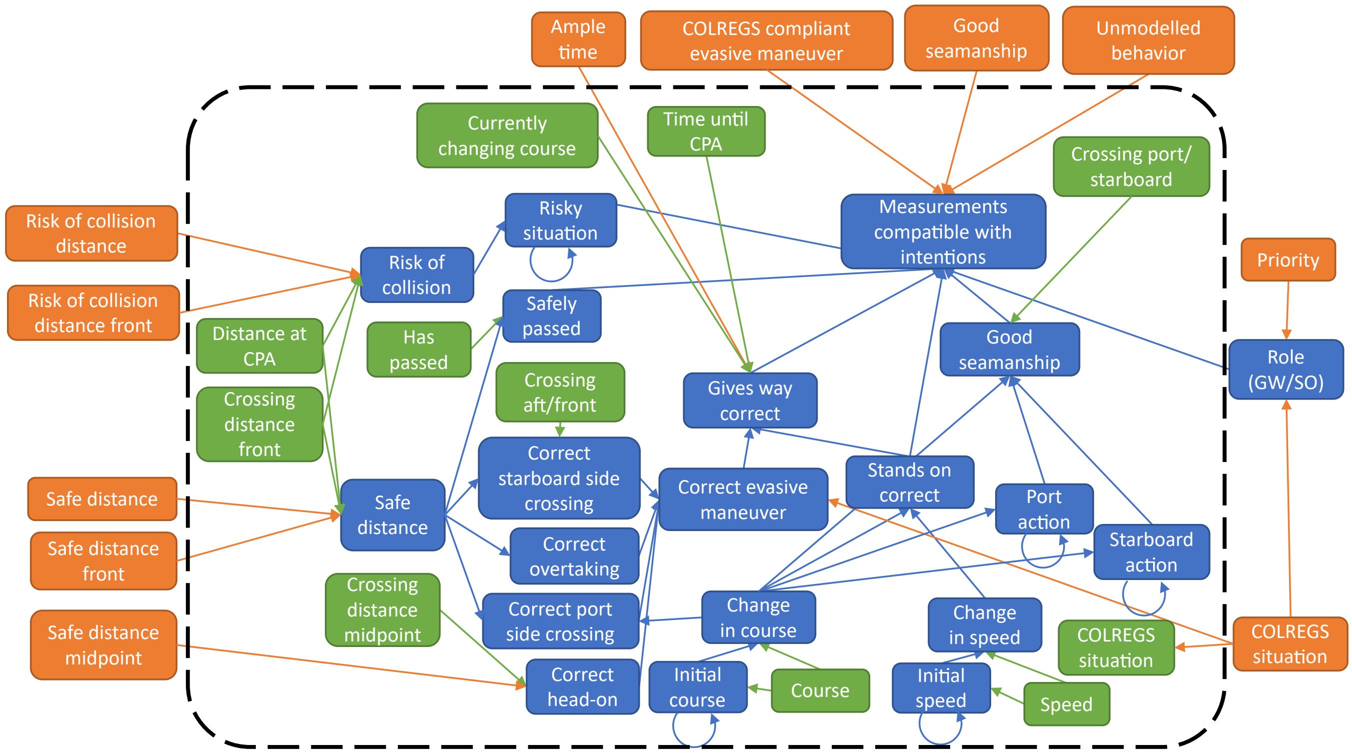

Fig. 2: Topology of the dynamic Byesian network (DBN) used as the intention model. Orange nodes represent intention states, green nodes measurements, and blue nodes model variables. The nodes within the dotted line are time-dependent, while the nodes outside are time-independent. Only the nodes within the dotted lines are repeated when a new time step is made. Nodes related to "situation start" are not shown.

distance. What constitutes a safe distance is uncertain and may depend on several factors.

- Situation started: The COLREGs situation and initial course and speed are defined when the situation starts. When the situation starts is unknown but becomes more likely as the ships get closer.
- COLREGs situation intention: Describes the probability of the ship behaving as if it is a head-on, crossing, or overtaking situation. The COLREGs situation is defined when the situation starts and is based on the relative heading and bearing between the ships. Uncertainty in the situation can stem from the ships having a relative heading or bearing that is close to the border between two situations, or if the situation changes while it is not clear if the situation has started.
- Risk of collision / risky situation: Whether there is a risk of collision is evaluated by considering how close the ships are expected to come at closest point of approach (CPA) if they keep their current course or speed. The situation is considered to be risky if there has been a risk of collision at some point since the situation started. If there is no risk of collision then no avoidance action is needed.
- COLREGs compliant evasive maneuver intention: This state indicates whether the ship appears to consider COLREGs when performing evasive maneuvers. This state does not change if the ship does not perform any evasive maneuver, which will instead affect intention priority higher.
- Good seamanship intention: This node considers behavior that is in compliance with the main rules but should still be avoided, such as changing which side an avoidance maneuver is made towards and changing course to cross at a shorter distance.
- Intention priority: A ship acting as if it has a higher priority will always stand on, while one acting as if it has a lower priority will always give way.

B. Modifications to the model

Some minor improvements to the model in [1] are proposed in [13]. This section presents the changes which are applied to the model used in this article.

The model presented in [1] did not handle measurements made during a course change. This was solved in [13] by introducing a new measurement of whether the ship is currently changing course. This measurement considers if the course change over the last 6 s is larger than $10°$. If the ship being modeled is currently changing course then it will be marked as giving way correctly.

Good seamanship was extended to require that if the ship being modeled changed its course to port then it has to pass the other ship on its starboard side, and vice versa.

A change that did not change the logic of the model but made it numerically easier to solve the network was

TABLE I: The initial distribution used for the intention variables. $\mathcal{N}(\mu, \sigma)_{[a,b]}$ indicates a normal distribution with expected value μ, standard deviation σ, truncated to be between a and b, and discretized into 30 evenly spaced intervals. The probability of "true" is given for binary states.

Intention node	Prior distribution
Ample time	See Figure 3
COLREGs compliant evasive maneuvers	0.99
COLREGs situation	Equal probability for all situations.
Good seamanship	0.99
Priority	$[higher = 0.05,$ $similar = 0.90,\ lower = 0.05]$
Risk of collision distance	$\mathcal{N}(1500\,\mathrm{m}, 250\,\mathrm{m})_{[0,2500]}$
Risk of collision distance front	$\mathcal{N}(1500\,\mathrm{m}, 250\,\mathrm{m})_{[0,2500]}$
Safe distance	See Figure 4
Safe distance front	See Figure 4
Safe distance midpoint	See Figure 4
Situation start distance	$\mathcal{N}(13\,000\,\mathrm{m}, 1000\,\mathrm{m})_{[0,15000]}$
Unmodeled behaviour	0.00001

TABLE II: Parameter choices.

Description	Value
Max change in course that is considered as keeping the course	15 degree
Max change in speed that is considered as keeping the speed	$1.5\,\mathrm{m/s}$

implemented. This consisted of removing states related to good seamanship and COLREGs compliant evasive maneuver from the definition of correct evasive maneuver and instead including them in the definition of whether the intentions and measurements are compatible.

V. Definitions and Prior Distributions

Initial distributions are given in Table I while parameter choices are given in Table II.

The distributions for "ample time" and "safe distance" are evaluated based on parameters extracted from the AIS data set by [14], [16]–[18]. Only the cases that are manually inspected and classified as being correct COLREGs situations are used. The resulting distributions are shown in Figures 3 and 4. Maximal ample time is set to $1800\,\mathrm{s}$ and maximal safe distance to $1500\,\mathrm{m}$. This ensures a large

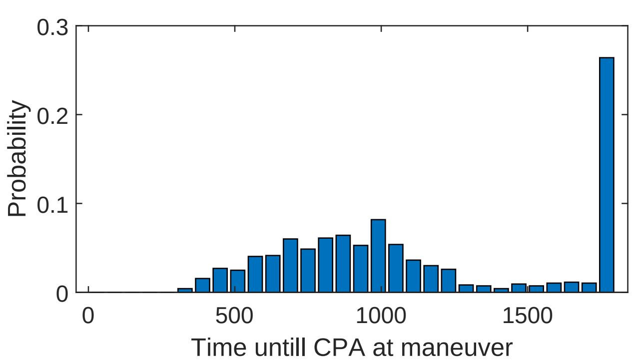

Fig. 3: Prior distribution for ample time extracted from historical AIS cases from outside the Norwegian coast.

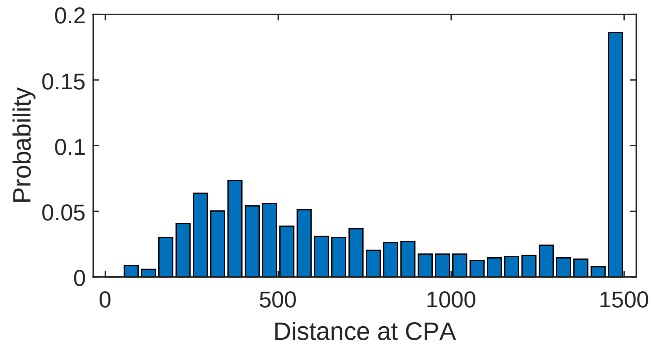

Fig. 4: Prior distribution for safe distance extracted from historical AIS cases from outside the Norwegian coast.

resolution on the times and distances relevant for collision avoidance. The last bin in the distributions becomes quite large as the distributions have very long tails exceeding the maximum value. These tails are very gradually decreasing and do not contain any subsequent areas of high probability density.

The distribution for "risk of collision distance" and "situation start distance" are not as easy to extract from the classified data. These are instead manually chosen to work well for the cases used to generate the results.

Including the course and speed of ships as nodes in the DBN requires discretizing the state. Discretization steps of $10°$ are chosen for the course and $0.72\,\mathrm{m/s}$ for speed (with an upper limit on $18\,\mathrm{m/s}$). This was the finest resolution that was feasible to use when discretizing using the GeNie software [20]. The course and speed change parameters given in Table I had to be chosen larger than their corresponding discretization step size.

VI. Result

This section presents the results of applying the intention model to six different encounter cases chosen from the AIS data set. Each encounter is played back with the intention inference module active. The estimated intentions for both ships in the encounter are presented. The encounter cases are manually chosen from the data set. Focus was placed on testing encounters where the main maneuvers of the ship relate to collision avoidance, and cases where it is interesting to infer the intentions.

Case 1 - Crossing correctly

Figure 5 shows two ships meeting in a crossing encounter. The red ship performs a COLREGs-compliant evasive maneuver at the $300\,\mathrm{s}$ mark. The higher priority intention of the red ship increases quite a lot before the maneuver as the maneuver is quite late compared to the ample time distribution. The probability that the blue ship will comply with COLREGs when performing evasive actions falls at the last two time steps due to the blue ship reducing its speed by 40% and turning its course a bit to port.

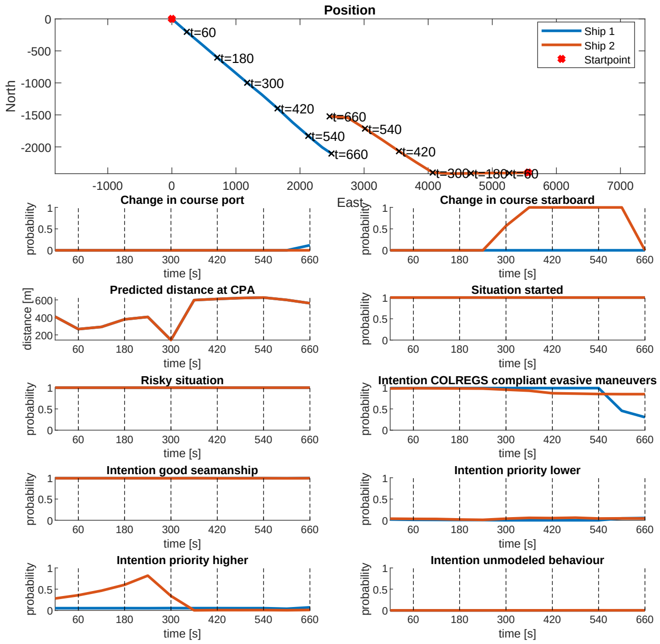

Fig. 5: Case 1 - Correct crossing situations.

Case 2 - Crossing incorrectly

Figure 6 shows a crossing encounter where the ship that according to COLREGs rule 15 has the stand-on role performs an early evasive maneuver. The course change is quite slow and small making the intention model evaluate a medium probability that the red ship has performed a starboard evasive maneuver and therefore acts as if it has a lower priority. The probability that the red ship intends to follow COLREGs when performing evasive maneuvers does not reduce much as the maneuver is in compliance with COLREGs rule 17c. The probability that the blue ship acts as if it has higher priority does not increase significantly even though it does not change its course or speed. This is due to the red ship already having acted which makes keeping the course and speed acceptable give-way behavior for the blue ship.

Case 3 - Head-on passing on starboard side

Figure 7 shows a head-on situation where the ships pass with each other on the starboard side which is contrary to COLREGs rule 14. The intention model infers that the red ship is as acting as if it has higher priority as it does not change its course or speed. The intentions of the blue ship are not as clear as it changes its course a bit back and forth, making the intention model switch between the ship acting as if it has a higher priority, performing an incompliant evasive maneuver, and showing unmodeled behavior. In all cases, good seamanship is quite reduced.

Case 4 - Head-on low risk of collision

Figure 8 shows a similar situation as in Case 3 but where the ships pass at a greater distance. In this case, the behavior is mainly explained by there not being a risk of collision, in which case the ships do not need to act. At the start of the

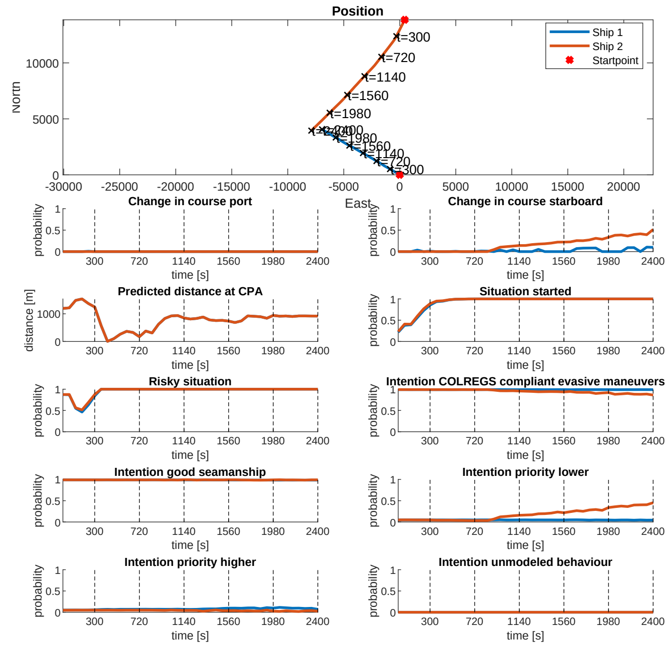

Fig. 6: Case 2 - Crossing situation where the wrong ship acts.

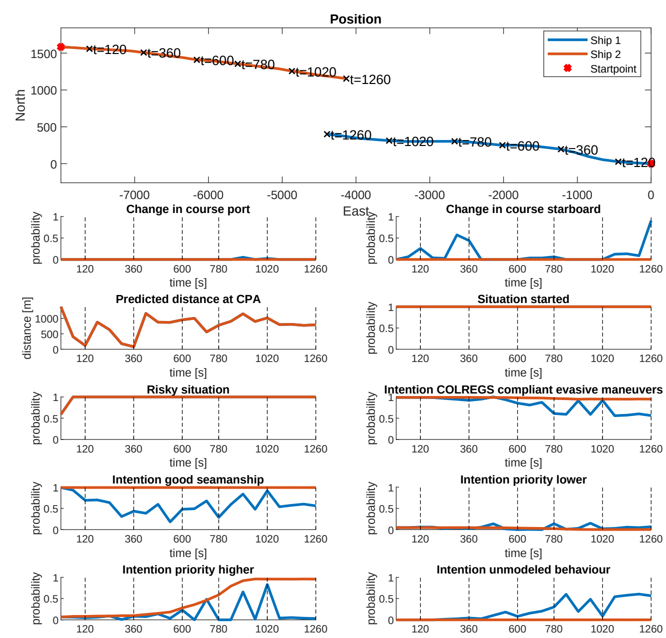

Fig. 7: Case 3 - Head-on situation where the ships pass with each other on the starboard side.

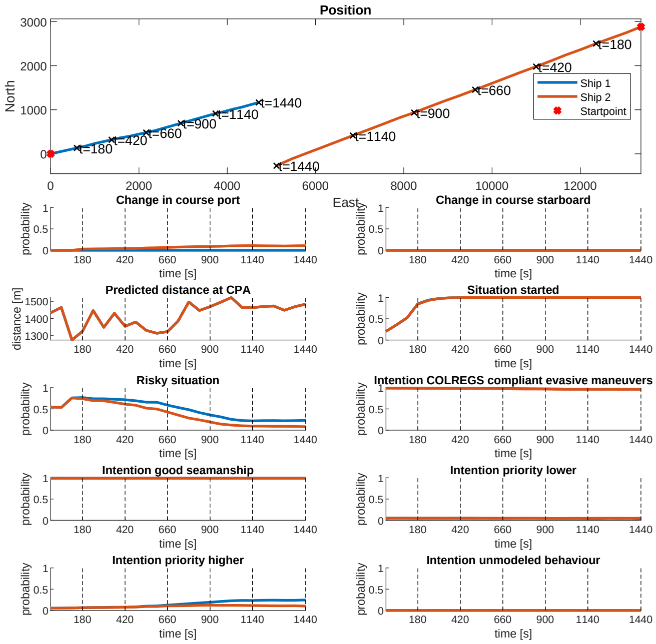

Fig. 8: Case 4 - Head-on situations where the ships pass on the wrong side at a large distance.

encounter, the model evaluates around a 75% chance that the ships consider that there is a risk of collision. As the ships get close without performing an evasive maneuver this probability gradually decreases.

Case 5 - Head-on port maneuver

Figure 9 shows a head-on situation where the ships actively change course to pass with the other on the starboard side, which is contrary to COLREGs rule 14a. The model correctly identifies that the ships are performing evasive maneuvers in a COLREGs incompliant manner.

Case 6 - Situation started

Figure 10 shows a situation where uncertainty about when the situation starts plays an important role. Before the 360s mark, the blue ship takes a starboard turn before it aligns back up on a collision course. The intention model assumes that the COLREGs situation started after this course change, after which the blue ship performs a late COLREGs incompliant evasive maneuver by crossing in front of the red ship. To get this result the situation start distance had to be reduced to $\mathcal{N}(5000, 750)_{[0,8000]}$. Without this change then the blue ship was marked as acting in an unmodelled manner as it turned towards a collision course.

VII. Discussion

The results show how the intention model manages to correctly identify when ships act in accordance with COLREGs, Case 1, and when this is not the case, Cases 5 and 6. Furthermore, they show that the intention model can distinguish between incompliant maneuvers, Cases 5 and 6, compliant maneuvers but the wrong ship acts, Case 2, and situations where no ship acts, Cases 3 and 4.

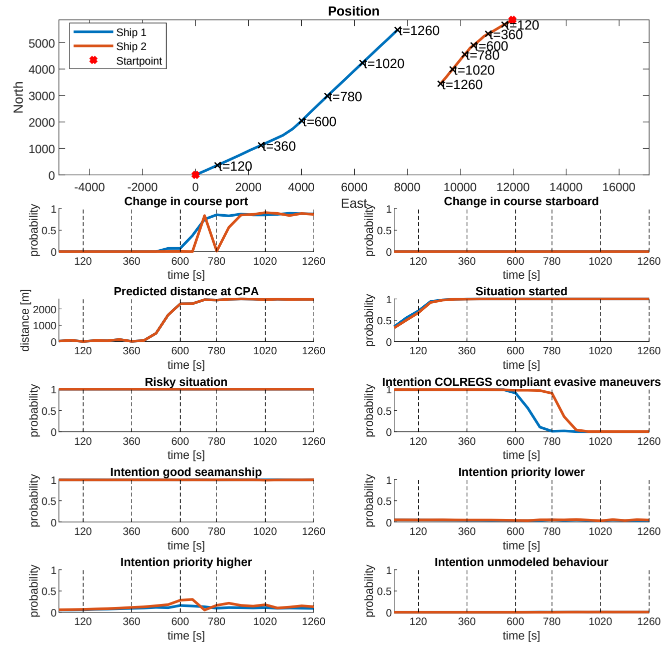

Fig. 9: Case 5 - Head-on situation where the ships act to pass on the incorrect side according to COLREGs.

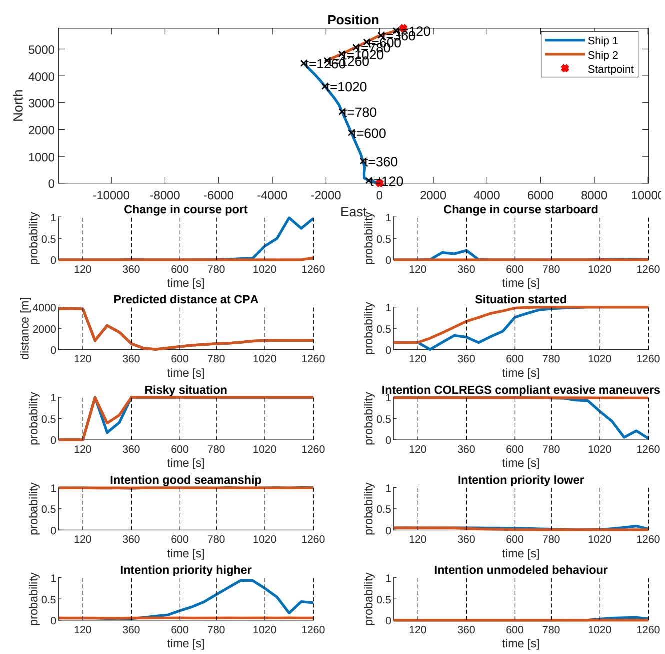

Fig. 10: Case 6 - Crossing situation where there is a maneuver change unrelated to collision avoidance at the start of the encounter.

The “ample time” distribution defines when ships, that have so far not performed a maneuver, will be marked as either having a higher priority, Case 3, or considering that there is no risk of collision, Case 4. In Cases 1 and 6 the probability that one of the ships acts as if it has a higher priority increases quite a lot before the evasive maneuver is performed. It might be that this apparently late behavior should be expected if the type of ships and location of the encounter is considered as well. Having separate distributions for different locations and ship types can enable the intention model to understand that, for example, small ships in inland areas tend to act later and come closer than large ships in open waters.

A limitation with the “ample time” definition is that it does not consider how difficult it is to perform the evasive action. Much earlier actions must be taken in head-on situations where there is a large offset to the wrong side, Case 4, than in for example crossing situation with no offset, Case 1.

Cases 3 and 4 shows the effect of the “risk of collision” distribution. Both present cases where neither ship performs an avoidance action. In Case 3 this is explained by the ship acting as if it has higher priority, while it in Case 4, where the ships pass at a larger distance, is explained by there not being a risk of collision.

The effect of the “situation start” distribution is shown in Case 6. Reducing the situation start distribution enabled the intention model to filter out a course change that was not related to collision avoidance. Having this low definition of when the situation starts would not work in other cases, such as Case 2, as it would then not realize that the red ship has actually performed an avoidance action. It might be that a different definition of when the situation starts is warranted in these two cases if one is for example near the coast while the other is in open waters. Alternatively, it might be inadequate to define when the situation starts from distance alone.

Modeling the “situation start” in the DBN has some advantages as shown in Case 6, but makes the model much more complex and requires that the initial heading and speed of the ship is included as nodes in the DBN. Introducing them as nodes requires that the heading and speed are discretized. The maximum number of discretization intervals that can be used in practice are quite limited as the computational burden of evaluating a DBN increases substantially with the number of intervals. Having few and large intervals is a problem when a ship starts with a course or speed close to the boundary between two intervals, then a small change in course in one direction can be marked as the ship changing course, while a larger course change in the opposite direction can be marked as the ship keeping its course. To limit this problem a quite large definition of how small speed and course change that are considered as standing-on is used. This is especially helpful in Case 4 where even though the red ship keeps a very steady course, the probability that the ship changes its course to port starts to increase. This large definition has limitations in Case 2 where it causes uncertainty about whether or not the red ship has performed a collision avoidance maneuver, even though it clearly has.

Cases 1 and 2 show an error in the inference where the probability that the ships will comply with COLREGs when performing evasive actions decreased a bit, even when the avoidance actions are in accordance with COLREGs. This error does not constitute a large problem as the reduction in probability is small, but it is an indication that something is wrong with the inference. The cause of this error has not been found, but it seems to not directly be related to the logic of the intention model itself. It rather seems to be related to the model being sensitive to numerical errors. Further investigation on understanding and alleviating this error is needed.

Another limitation observed during testing, but not present in any of the presented cases, is that having a safe distance to the current midpoint in head-on situations, as defined in [1, Eq. 11], is not enough if the ships meet at a relatively large bearing angle. This can be solved by requiring that the ships in addition must have a safe distance and pass at the correct side at CPA.

VIII. Conclusion

In this article, the intention model developed in [1] is tested on historical data using empirical distributions. The tests demonstrate that the model is able to identify different ways the ship’s behavior can conflict with the rules, either by acting as if they have higher or lower priority, giving way in an COLREGs incompliant manner, or by not considering it a risk of collision.

This research has also demonstrated some weaknesses with the model that opens up for further work. The main limitation is with filtering out actions unrelated to collision avoidance. The current implementation that considers whether the situation has started can handle some cases but makes the model more complicated and introduces discretization issues. Finding a better solution would substantially improve the model. Furthermore, a new method for ample time that considers how difficult the avoidance maneuver will be, is warranted. Lastly, the model does not handle actions not related to collision avoidance, such as avoiding grounding or following a traffic separation scheme or narrow channel.

Acknowlegement

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