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Identifying and Analyzing Safety Critical Maneuvers from High Resolution AIS Data

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ABSTRACT: We demonstrate the value in previously disregarded parameters in AIS data, and present a novel way of quickly identifying and characterizing potentially safety critical situations for vessels with a properly configured AIS transponder. The traditional approach of studying (near) collision situations, is through vessel conflict zones, based on vessel location and speed from low resolution AIS data. Our approach utilizes the rate of turn parameter in the AIS signal, at maximum time resolution. From collision investigation reports it is often seen that prior to or at collision navigators perform frenetic rudder actions in the hope to avoid collision in the last second. These hard maneuverings are easily spotted as non-normal rate of turn signals. An identified potential critical situation may then be further characterized by the occurring centripetal acceleration a vessel is exposed to. We demonstrate the novelty of our methodology in a case study of a real ship collision. As the rate of turn parameter is directly linkable to the navigator behavior it provides information about when and to what degree actions were taken. We believe our work will therefore inspire new research on safety and human factors as a risk profiles could be derived based on AIS data.

1 INTRODUCTION

The Automatic Identification System (AIS) is an automatic tracking system for identification and location of vessels by exchanging data via VHF communication to other nearby ships, AIS base stations, and satellites. It has become mandatory, through the International Maritime Organization [1] (IMO), for commercial vessels over 300 GT since 2004 affecting approximately 100.000 vessels. Additional legislation from the EU and the US extended the requirements for having an AIS transmitter on board also to smaller crafts such as fishing boats. It is estimated that in 2012 there were a quarter of a million vessels equipped with AIS and that this number will rise to over a million in the near future, as per Wikipedia (2015). Since AIS transponders use VHF communication the reliable range is about 10-20 nautical miles, although AIS satellites can pick up AIS signals from space. The original purpose of AIS was meant as an aid to collision avoidance but many other applications have since been developed such as fishing fleet monitoring, vessel traffic services (VTS), maritime security, fleet and cargo tracking, search and rescue, accident investigation among others. In addition to the increase in the number of AIS transponders, there is an extensive effort, both commercially and by governments, to increase; the global coverage of the AIS signal and the volume

[1] http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx

receiving capabilities of satellites, base stations, and data stores[2]. This follows the Big Data trend, and additional insights may be gained from high time resolution AIS data.

AIS is an important source of information for studying maritime traffic and associated critical situations, in particular ship-to-ship collisions. Most studies on risk of ship-to-ship collisions are based on identification of potentially critical collision situations in the AIS data. Interestingly, neither IMO nor courts state explicit criteria defining critical situations or collision risks. The closest definition of a near miss by IMO is ″a sequence of events and/or conditions that could have resulted in loss. This loss was prevented only by a fortuitous break in the chain of events and/or conditions.″ (IMO (2008)). According to Sturt (1991), ″... that must always be decided, according to the circumstances of each case, by men of nautical experience″. This means the interpretation of near-collisions is almost totally subjective as it will depend on the ″comfort zone″ of the involved parties. One master may consider a certain distance as safe enough whereas others may not. Also, the acceptable minimum distance between vessels will most certainly depend on the size of the vessels, their (relative) speed, their maneuverability, maybe their cargo and of course on a number of occurring circumstances such as sea state and weather conditions. All these factors will influence what is considered as ″close quarters″ or the size of the comfort zone.

Considerable effort has been put into deriving an operational concept that defines a domain around a ship that would constitute a ″vessel conflict zone″, i.e. a geometric area where there is a probability of collision. The sizes and shapes of theses domains range from very simple to quite complex structures, some are circular, elliptical or polygonal, some are static, and others are dynamically resized depending on the speed of the vessel, e.g. Fujii & Tanaka (1971), Goodwin (1975), Coldwell (1983), Zhao et al. (1993), Pedersen (1995), Mestl et al. (2008), Pietrzykowski (2008), Pietrzykowski & Uriasz (2009), Wang et al. (2009), Zhang et al. (2015) in order to make the term ″near collision″ and ″comfort zone″ more tangible and quantifiable.

So far the available approaches for identification and quantification of critical situations are either in form of a subjective zone or on a numeric ″fear factor″ as per IMO (2015), expressing the perceived risk of a close encounter. The validity of the zone-approach has already been questioned in the literature as the intended vessel movement, background traffic, ship type and hydro-meteorological conditions should also be taken into account when determining whether a dangerous situation occurs or not, Goerlandt et al. (2012), Kao et al. (2007), Montewka et al. (2011). It may also be pointed out that all the traditional approaches are quite complex, not only in the construction of the zone and fear factor, but they are also quite computational intensive when trying to identify potential crossing of ship trajectories. To keep the computational work load manageable all these approaches utilize down-sampled AIS data, i.e. usually 6-10 minutes time difference between samples, and they only use the geo-locations of the vessel. Other relevant parameters offered by the AIS signal are to a large extent neglected.

In this paper we will present a new approach that allows identifying potential critical situations rather quickly, in historical time series of AIS data. This method utilizes high resolution AIS position data, and the rate of turn parameter available in the data stream. The next chapter presents a case study of an actual ship collision found in our data material, demonstrating the advantage of rate of turn (ROT). We derive a general outline how to identify non-normal maneuvering and their characterization. The paper is concluded with some critical remarks about our approach, and open a discussion regarding potentially necessary steps the IMO or other authorities may want to take to increase the benefits offered by AIS data.

2 METHODOLOGY

2.1 *Identification and characterization of (near) collisions by navigational parameters*

In the following we will outline a new approach for identification and characterization of (near) collision situations that utilizes high time frequency AIS data (2-12 second sampling rate) using the following parameters: latitude, longitude, rate of turn (ROT), speed over ground (SOG), and course over ground (COG). Note that the ROT does not represent the rudder angle per unit time, but the actually occurring change in heading of the vessel, as per IMO (2003). We have chosen to present the detailed findings of a single incident to demonstrate the feasibility of our method. It is left to future studies to estimate near collision frequencies in Norwegian waters.

The following excerpt from a near-collision incident report underlines why we consider the ROT as of one of the most interesting AIS parameters. It was issued by the The Transportation Safety Board of Canada (1998), describing the circumstances around the near miss between the cruise ship ″STATENDAM″ and the tug/barge ″BELLEISLE SOUND″/″RADIUM 622″ in the Discovery Passage, British Columbia on 11 August 1996: ″The hard-a-starboard maneuver caused the ″STATENDAM″ to heel over to port, and resulted in some minor injuries to six passengers and two of the crew. ...″. Our approach is based on the observation that any near collision or actual collision is usually accompanied with some frenetic activity right before the (near) collision in the hope to avoid it. Many critical situations evolve because the navigators assume/expect that the other party will do the necessary maneuvers for collision avoidance. Even if the vessels can no longer avoid a collision the navigator(s) will nevertheless try to turn the wheel in the seconds before the impact in the hope this will diminish the consequences. This means, in situations where the navigator has realized that a situation may become critical he/she will turn the wheel trying to avoid the criticality. In these situations relative high

[2] See e.g. companies such as VesselTracker, Orb-Comm, exactEarth, Spire etc.

ROT values should be observable in the AIS data. Thus, we may anticipate that the closer a potential collision is in time and/or distance, the more intense will be the navigational action of one or both helmsmen. Due to the usually large inertia and momentum of ships, changing the speed of a vessel is generally not considered an option resulting in fast changes. The ships response to the rudder is usually much faster (depending on the speed). According to rule 8 in COLREG - Preventing Collisions at Sea (IMO (1972)) it is stated that "Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance." No practically usable information is given regarding the safe passing distance except that "it depends on the circumstances" and that "the person on the other vessel should not feel compelled to act also to increase the distance further." In this respect we could claim that our approach based on ROT is actually in alignment with this fuzzy IMO requirements as it actually focuses on the (rudder) action taken "to increase the distance further " Llana & Wisneskey (1991).

2.2 *Close up study of a collision between a ferry and a fishing vessel*

The Norwegian Coastal Authorities kindly provided DNV GL with a high resolution AIS data set for research purposes. We will therefore anonymize the presented data as much as possible, i.e. remove reference to the involved parties, time of occurrence and geo-location.

The following collision occurred in open waters, far from a port, in Norwegian waters recently. Fortunately there were no injuries or pollution, nor were there any significant material damages. According to the investigation report, on a summer morning (08:45, local summer time), a fishing vessel in transit crossed the trajectory of a larger ferry (on regular route) from a port. The helmsman on duty on the ferry was busy outside the bridge and the lookout, not possessing a bridge certificate, alerted the helmsman too late. According to the administrating director of the ferry line: "...a number of maneuvers were performed leading to a considerable heeling of the vessel which is quite normal when using the rudder a lot...". This statement gives again an indication that there must have been quite a high rate of turn of the ferry.

Figure 1 shows these vessel traces with a low (5-10 min. sampling rate), i.e. traditional, and high frequency (2-10 sec. sampling rate) AIS data feed. Based on the low resolution signal, it is indeed quite difficult to determine whether a critical situation occurred or not. Right before the incident, the ferry had a speed of 18 knots and an AIS sample was sent on average every 3 seconds. For the fishing vessel, traveling at 8 knots, the AIS sampling interval was 11 seconds. The trace clearly indicates that the fishing vessel did not show any evasive maneuvers before the impact, whereas the ferry reacted too late. The collision time can be extracted from the latitude/longitude parameters or the COG parameter in the AIS data feed.

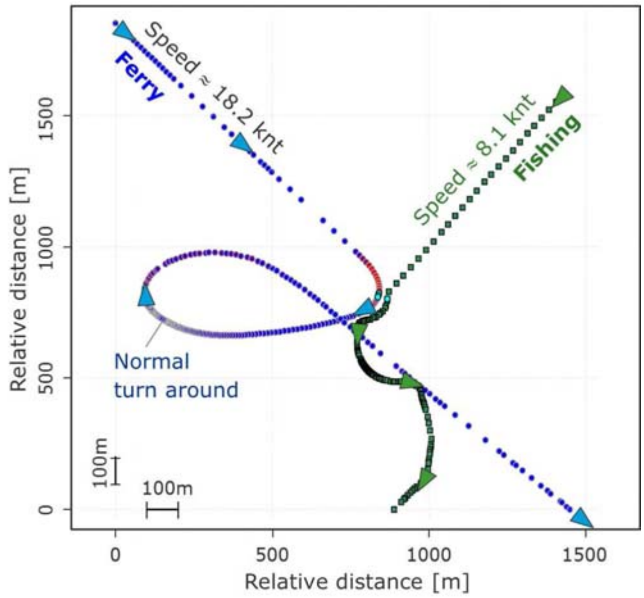

Figure 1. Visualization based on high resolution AIS data, overlaid with the low resolution AIS data points (blue triangle - ferry, green triangle - fishing vessel). Note that the ferry's low resolution AIS point at the "normal turn around' could be mistaken as an outlier. The high resolution trace of the ferry is color coded according to its rate of turn (blue low ROT, red high ROT). The collision points in their traces are indicated with cyan dots.

The top panel in Figure 2 shows the COG for both vessels.

Note that the fishing vessel shows no sign of evasive maneuvers until collision which appears as a sudden change in COG, coinciding with that of the ferry. We can therefore deduce that the collision occurred between 7:23:00 and 7:23:07 (UCT) on that morning. The AIS transmitter's sampling rate depends on velocity and turn rate, with a maximum of 2 samples pr. second for high velocity or turn rate. Thus, due to the relatively low speed of the fishing vessel, the corresponding AIS sampling interval was not at maximum, hence the ~ 7 seconds uncertainty in the collision time. Observe also that the fishing vessel (~ 300 GRT) felt the impact much more than the ferry (~ 5700 GRT), hence the noticeable change in COG.

The bottom panel in Figure 2 shows the ROT of the ferry. Unfortunately the fishing vessel was not setup to log ROT values. Notice the high peak in the ROT indicating a hard starboard (positive values) maneuver right before the collision revealing the futile attempt of the ferry navigator to avoid collision. In the 7 seconds time uncertainty of collision time, the ferry sent three AIS samples due to her higher AIS sampling rate (shown as cyan dots). It is not surprising that the high rate of turn was felt slightly uncomfortable by some passengers, as the comfort limit for cruise ships (at 20 knots) is considered 10 deg. pr. min in ROT, as per The Transportation Safety Board of Canada (1998). The evasive maneuver of the ferry (at 18 knots) was far above that limit. In order to relate the trace and COG to the occurring ROT, the corresponding trace (see Figure 1 and COG (see Figure 2 bottom panel) of the ferry was color coded based on her ROT (maximum measured ROT = 194.5 deg/min and ROT = 0.0 deg/min are color coded red and blue respectively).

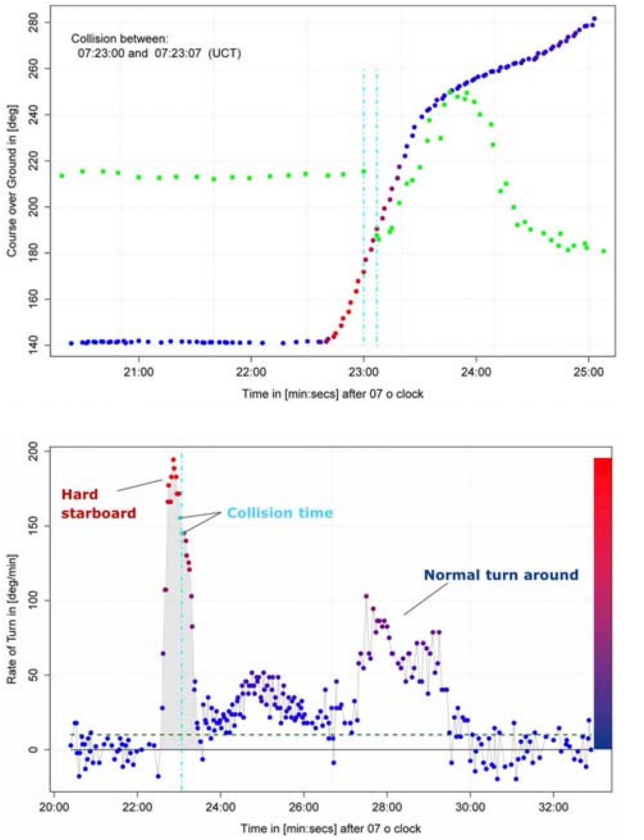

Figure 2. TOP - Course over ground (COG) for both vessels (green squares - fishing vessel, blue/red dots - ferry). Observe that the COG for the fishing vessel remained unchanged until collision, after which it changes abruptly and parallels with that of the ferry (also seen on the geo traces in Figure 1). From the changes in COG, the collision must have occurred between 7:23:00 and 7:23:07 (UCT) as indicated with the cyan dash-dotted lines. BOTTOM - Rate of turn (ROT) of the ferry in deg/min. Observe the high peak (hard starboard maneuver) right before the collision. The red and blue color bar represents high and low values of ROT respectively. For comparison, the green dashed line represents the ROT comfort limit for cruise ships traveling at 20 knots. Thus, it may not be surprising that the ferry maneuvers were experienced as slightly uncomfortable by passengers.

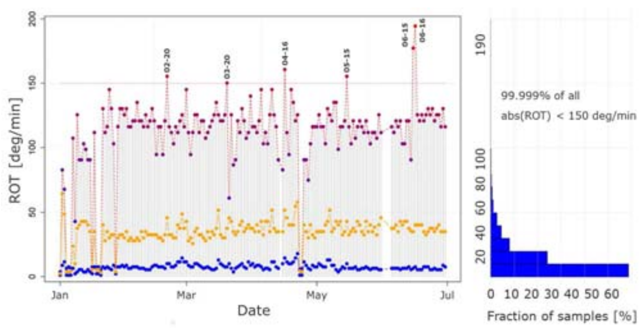

Figure 3. LEFT - The daily maximum |ROT| values (upper red dots), the daily median |ROT| values (blue dots), and the |ROT| values corresponding to the 95 % percentile (orange dots) of the ferry over half a year. Only ROT /= 0 were taken into account. The highest ROT peak relates to the collision with the fishing vessel. The relative high peak the day before corresponds to a sharp maneuvering during the passage between a group of islands (see Figure 4). It is easy to pick out any non-normal maneuvering from this single ship time series plot. Here all |ROT| ⩾ 150 deg/min are tagged with the date of occurrence. RIGHT - Frequency of occurrence of various |ROT| values. Note that 99.999 % of all |ROT| ⩽ 150 deg/min.

2.3 *General approach for identification and characterization of (near) collisions*

The case example in Section 2.2 clearly demonstrated the value of the ROT parameter in the AIS data feed. In the following we show how potentially critical situations can be identified quickly. We then turn our attention to characterizing these situations.

Figure 3 shows the various daily maximum ROT values of the ferry over half a year, close to 2 million samples for the full dataset. Each vertical line represents one day. In Figure 3, it is seen that for some days the ferry stayed in port, giving only zero values, whereas no samples were available over a number of days period in April. The highest peak in ROT relates to the collision of the ferry with the fishing vessel. Interestingly, there is also a relative high peak the day before which after a closer examination turns out to have been a very sharp and definitively a non-normal turn when navigating through a group of islands. This is shown in Figure 4, where the track has been color coded according to the ROT. Notice the very high values along the sharp turn, compared to more normal behavior on previous passages. This might have been a situation where a non-AIS emitting object was encountered, since no other vessels where present nearby. The bar plot in the right panel in Figure 3 is a histogram showing the frequency the various ROT's occurring over half a year. A ROT value above 150 deg/min is very rare, i.e. 99.999 % of all samples were below this value. Note that this is not the fraction of safe passages, but the number of ROT signals above the 99.999 % quantile for that vessel. A high ROT can therefore be considered as an indication of a potentially non-normal maneuvering. The time of its occurrence can be obtained from the time series plot. A measure for sensitivity of detection of non-normal navigational maneuvers based on ROT is given by a high signal to noise ratio. By using max(|ROT |)/median(|ROT |) ~ 36, we see that the collision incident was far above what is expected as a normal ROT fluctuation. There were four other occasions where the |ROT | > 150 deg/min, i.e. on 20th February, 20th March, 16th of April and 15th of May. A closer inspection indicates that most of these high ROT's were single occurrences which may be regarded as outliers, see for example Figure 8 in Section 3.2.

Large ROT's are necessary but not sufficient indicators of potential evasive maneuvers. A further characterization of an identified high ROT is its associated centripetal acceleration (CA), i.e. change in rotation around the vertical axis. This acceleration is of interest as passengers will be exposed to it when the ship is turning. The magnitude of centripetal acceleration is defined as

$$CA = \frac{SOG^2}{R} \tag{1}$$

where R is the turn radius. The time T it takes for a vessel with speed SOG to complete a whole circle with radius R is

$$T = 2\pi \frac{R}{SOG} \tag{2}$$

which must be the same time it takes for the vessel with a constant ROT to complete a whole circle, i.e.

$$T = \frac{2\pi}{ROT} \tag{3}$$

Equaling both expressions of T , solving with respect to R, and inserting it into Eq. (1) we get an expression for the centripetal acceleration (CA) in terms of ROT and vessel velocity SOG:

$$CA = \frac{SOG^2}{R} = SOG \cdot ROT \tag{4}$$

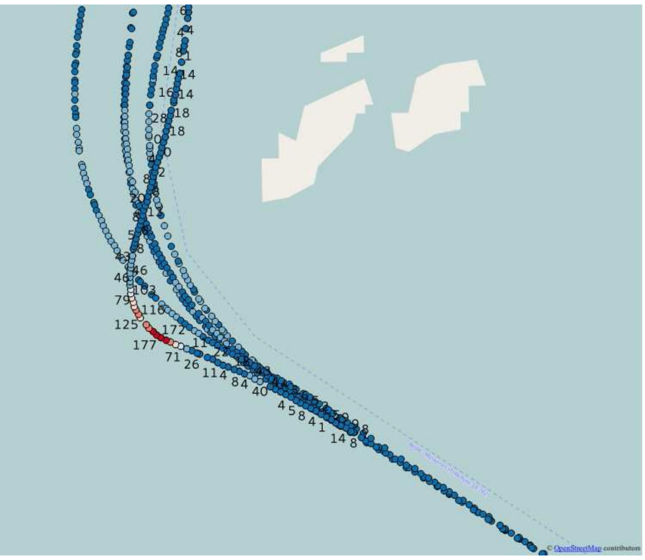

Figure 4. AIS track of a ferry navigating through a group of small islands. The track has been color coded according to the rate of turn (blue - low ROT, red - high ROT). Note the very large ROT values of the lowermost track compared to the more normal values on previous passages around the islands.

The advantage of using the CA is that it directly relates to the human perception of comfort. A daily maximum plot of CA values for the ferry are shown in the left panel in Figure 5. The stated maximum ROT = 10 deg/min as the comfort limit on cruise ships at 20 knots, as per The Transportation Safety Board of Canada (1998), translates to CA = 0.03 m/s^2 , and is shown by the green dashed line in the left panel. It may be questioned if the CA comfort limit of a cruise ship is directly transferable to a relative small ferry navigating in harsh seas. On such a ferry, passengers may have to expect larger vessel motion, i.e. rolling and stamping but also higher turn accelerations. In contrast to the ROT, which directly measures an evasive maneuver, the CA may be considered a measure of passenger comfort. From the CA time series in Figure 5, we can see that in addition to the previously identified occurrences of high ROT's we have high CAs on a number of other days as well, e.g. 9th January, 27th March, 10th April, 9th May and 22nd June. Due to a lower speed over ground, the occurrence of a high |ROT| on 15th of May (seen in Figure 3) does not coincide with a corresponding high |CA| at the same date. Defining a signal to noise ratio similar to what was done to |ROT|, i.e. max(|CA|)/median(|CA|) ~ 40, we see that the centripetal acceleration gives a slightly better detection performance. The bar plot in the right panel in Figure 5 is a histogram showing the frequency the various |CA|'s recorded over half a year. A |CA| value above 0.35 deg/min is very rare, i.e. 99.999 % of all samples were below this value.

The degree of discomfort a passenger may experience, will not only depend on the magnitude of acceleration, but also on how long it will last. A high acceleration over just a few seconds may be felt as a sideways bump and may rather be considered as annoying as one might spill the drink. On the other hand, a high centripetal acceleration over an extended period of time, could result in considerable heeling of the vessel. By integrating all CA peaks in time, above a given threshold, one obtains a useful metric for passenger/crew discomfort. This quantity is then proportional to the impulse experienced when a ship turns. As we are only concerned about safety critical situations, which are characterized by excessive maneuvers, this threshold may be defined e.g. as those cases where both the |ROT| and the |CA| are above their 99 % percentile.

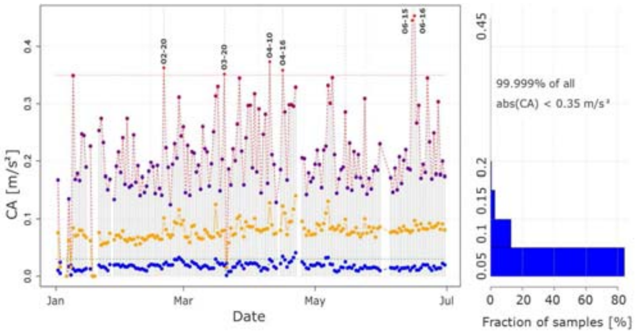

Figure 5. LEFT - Time series of daily maximum |CA| over half a year, only CA /= 0 were taken into account. The comfort limit for cruise ships is given by the green dashed line. Similarly to Figure 3, max(|CA|), median(|CA|), and 95 % quantile are color coded by red, blue and orange dots respectively. In the time series, some pronounced acceleration peaks (tagged with the date of occurrence) are different from those in Figure 3. Interestingly, the high |ROT| on the 15th May has a much lower corresponding CA (vertical gray dashed lines indicates extreme values from ROT in Figure 3). RIGHT - Histogram of the acceleration values with the corresponding fraction of samples on the x-axis.

This measure may be useful for providing a general characteristic of how a captain handles the ship.

3 RESULTS AND DISCUSSION

3.1 *Underlying causes of extreme values in ROT and CA*

The result of a closer investigation of the emphasized dates from Figures 3 and 5 is given in Table 1. The chosen dates correspond to occurrences of high |ROT| and |CA| values, that is, values above the corresponding 99.999 percentiles (|ROT| > 150 deg/min and |CA| > 0.35 m/s^2). Note from Table 1 that the collision sticks out for both ROT and CA. A high ROT may give a first but not sufficient indication of a potential non-normal maneuvering. For example, the high |ROT| on 20th of March and 15th of May occurred during heavy sea maneuvering. It is therefore difficult to use a single measure reliably, in order to identify and characterize non-normal maneuverings. However, both the ROT and CA measures, possibly combined with the impulse measure described in the previous paragraph, will provide valuable information about various navigational aspects. The scan for large ROT values is computationally cheap and effective, for a first narrow down of large data sets. As an example, the data set in our case study was reduced from 2 million points to only 6, which then can be further analyzed. For this particular ferry no other near collision incidents could be identified neither with our methodology, nor with the traditional zone approach over the half year. This is not surprising, since the navigators' task is to avoid (near-) collisions.

Our methodology flags all non-normal maneuverings which may however not always represent safety critical situations. As pointed out previously, it is also important to realize that non-normal maneuvers may occur even when there are no other vessels nearby. For instance, a floating container, fishing nets or a leisure boat may force the helmsman to suddenly change course. Illustrative examples are shown in Figure 6. It seems that this ferry had to turnaround in a hurry, hence the high ROT. If we take into account the time of year, i.e. early spring in Norway (8th May), late evening (21:53 oclock), its coastal location (remote area), and the fact that the vessel leaves the harbor again just after a 3 minutes stay, one may conclude that the ferry was probably empty and it turned around to pick up a late car arrival. By taking into account the ferry liners arrive and departure schedule, it turns out that the situation was rather critical for the car, as the last ferry departure was scheduled for 21:45. Such a turnaround is a common phenomenon in remote Norwegian coastal areas, and may rather be classified as customer service.

3.2 *Ship specific dependencies of ROT and CA*

Note that the maneuvering measures, i.e. ROT and CA, will be vessel specific (Bertram (2000); Rawson & Tupper (2001)). A small ferry vessel is much more maneuverable than a large tanker or freight ship. Hence, the range of ROT and thereby also CA will be quite different. The top panel in Figure 7 shows the different observed ROT values for a small ferry compared to a large tanker, randomly selected in our dataset. By comparing the distributions, it is evident that the ferry has a larger spread of the ROT values, implying higher maneuverability. Note also that the a ships ROT will not only depend on ship characteristics, but also on the sailing pattern, e.g. navigation through archipelago versus open sea.

Consequently, one has to be cautious when comparing these measures between vessels. Only vessels of the same size, draught, maneuverability may be compared. The bottom panel in Figure 7 shows the dependency between ship length and the average maximum |ROT| values, for all vessel types, in our dataset. Roughly 1000 vessels are included in this statistical average, i.e. all vessels in our database with a meaningful ROT signal. This dependency of ROT on vessel characteristics makes it more cumbersome to identify extraordinary maneuverings, as one has to define, for each individual vessel (or groups of similar vessels), "normal" maneuvering behavior. This also means that enough samples must be available in order to establish normal behavior.

Figure 6: LEFT - Position trace of a RO-RO vessel, color coded according to the ROT (high ROT - red, low ROT - blue), imposed on a map. A sharp turnaround, with a high ROT is visible, which most probably is not an emergency situation. Taking the time (8th May, 21:53) and the following short stay in port (~ 3 minutes) into account, it rather indicates that the vessel was empty and had a late customer pick up. RIGHT - Regular tracks of a ferry in gray (over half a year), indicate that the normal path is straight ahead. An unusual maneuver, as detected by our algorithm (color coded according to the ROT) is also shown. This may indicate that an obstacle (non-AIS emitting object, e.g. fishing net) was encountered, causing correction of course compared to the normal behavior.

Table 1. Summary of potential non-normal navigational maneuvers with high heeling. The collision event on the 16th. June sticks out with a very high ROT and a high CA. The island passage on the 15th. June, however, must have felt almost equally uncomfortable. None of the other candidates are in the vicinity to these events.

Date	$\|ROT\|_{max}$ [deg/min]	$\|CA\|_{max}$ [m/s²]	Maneuver duration [s]	Avg. wave height [m]	Comment
20th Feb.	155.4	0.36	6	2.6	Yawing in heavy sea
20th Mar.	150.2	0.34	49	1.9	Turn in heavy sea
10th Apr.	145.0	0.37	4	2.3	Sharp turn in heavy sea
16th Apr.	160.7	0.36	11	3.4	Yawing in heavy sea
15th May	155.4	0.28	71	2.0	Sharp turn in heavy sea
15th Jun.	177.2	0.45	60	1.0	Sharp turn
16th Jun.	194.5	0.44	60	0.8	Collision

3.3 *Dependence between ROT and CA on sea state*

Obviously, a small fishing vessel will also be more exposed to rough seas, requiring more rudder actions than a large freighter. The characteristics of the ROT values may therefore also show seasonal dependencies. The effect of waves on the ferry's ROT fluctuations, previously described in our case study, is given in Figure 8 below. Here it seems that the large rudder actions stem from navigating in high seas. Especially in situations when a vessel encounters a following or quartering sea, a phenomenon called yawing occurs, where the vessel exhibits side to side turning requiring large ROTs to stay on course. This is exactly what can be observed in the ROT and SOG series shown in Figure 8. The centripetal acceleration CA is proportional to the product between ROT and SOG, as seen from Eq.(4). Thus, in a rough sea, both ROT and SOG will depend on the sea state. It is therefore interesting to investigate if the rate of change in CA (time derivative) gives an indication of the sea state condition. The time series in Figure 9 shows the maximum wave height, measured over four daily time intervals, together with the maximum of the time derivative of CA, over the same time period. Only ROT and CA samples stemming from voyages were used, i.e. all harbor stays were excluded. Interestingly, there is indeed a significant co-variation (dependency) between the maximum wave height and the maximum rate of change in CA. The smoothed lines in Figure 9, is found to have a correlation coefficient of ~ 0.6. This observation could indicate that the AIS signal may actually be used to derive information about the currently occurring sea state. This information could, in some cases, be used to rule out some of the potential candidates for critical maneuvering, since some of the high ROT values could then be ascribed to maneuvering in heavy seas.

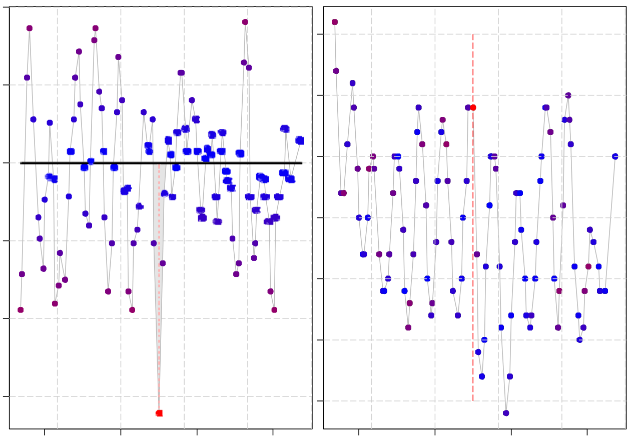

Figure 8. There was a rough sea on 16th of April with a recorded average wave height of 3.4m. LEFT Rate of turn plotted versus time. Large rudder actions compensating for the impact of the waves are visible. A single maneuver caused an extreme ROT value of magnitude 160.7 [deg/min], as indicated by the red dashed vertical line. RIGHT - The variation in speed over ground with time, shows the ferrys fatiguing course through the waves. The red dashed vertical line corresponds to the time of the extreme ROT value, shown in the left panel.

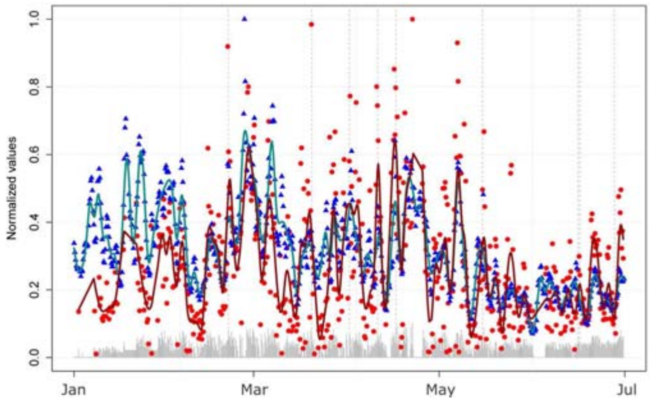

Figure 9. Normalized maximum wave height (at 4 different times a day, blue triangles) and normalized maximum rate of change in CA (at the same time period of day, red dots), together with fitted smoothing splines in the same colors (smoothing parameter 0.2). Observe the nicely visible co-variation of the smoothed signals. The gray bars at the bottom indicate the number of AIS samples available in the various time periods (max. 9700 samples/period).

4 CHALLENGES

4.1 *Critical situations does not always imply extreme ROT*

A fundamental challenge with our methodology, is the fact that only critical situations where non-normal maneuvers have been performed can be identified. In cases were the navigator fell asleep, or a situation was erroneously considered as not critical or in sudden groundings, no evasive maneuvers will have occurred and therefore no non-normal ROT signals will be observable. To identify these cases one may have to fall back to the traditional (and time/resource intensive) approach of analyzing overlapping zones between ships. In cases of groundings a sudden drop of the speed over ground to zero are relatively easy to identify. The reader must also realize that the ROT will be vessel specific, i.e. smaller vessels like fishing boats are much more maneuverable and will therefore exhibit normally larger ROTs (and CAs). On the other hand, for large vessels it may be almost impossible to see large ROTs due to their inertia and momentum. This means, in order to determine whether a non-normal maneuver has been performed one should not base this decision on single ROT values in isolation, one has to know the normal behavior for that vessel. Once normality is established, from representative historic ROT data, a given ROT can then be benchmarked against the normal behavior for that specific vessel (or group of similar vessels). It should also be pointed out that during the maneuverability tests of a new vessel, as demanded by IMO, an upper |ROT| value, valid in calm sea, will be recorded. If, during an operation, a ROT shows to be close to this upper limit, one may anticipate that indeed an extraordinary rudder action has been performed. We also showed that a high ROT can occur in rough seas. An indication about the sea state can be derived by computing the rate of change in CA. Further verification of these findings and a more elaborate study is left to future work.

4.2 *The Big Data problem*

In Section 2.1 we demonstrated by a case study how the ROT parameter in a high resolution AIS signal for a single ship can be used to identify non-normal behavior. Certainly, this path is always faster compared to more standard approaches of identifying near collisions, i.e. computing the minimum geographical distance of one vessel to its nearest neighbors in time. The success of the ROT approach assumes that an evasive maneuver was initiated and that the ROT indicator is properly setup with the AIS transponder.

Identifying values above a threshold for a single time series of 2 million points is straight forward on a regular desktop computer. Also for a small ship owner, it is not very challenging to handle full resolution AIS data for his fleet. However, our test dataset contains records for roughly 16,000 vessels for half a year. If this is the starting point, and maybe expanded to cover a time span of several years, it is not straight forward to store and handle all the data due to its volume. To overcome this challenge, the AIS signals have been stored in Apache HBase (scalable no-SQL database) on a Hadoop cluster, allowing fast and scalable analysis on shore. The example case considered in this study was identified both trough looking at ROT values alone, amongst all vessels, and by running a more complex algorithm to identify minimum distance between nearest neighbors. We defer further details about this work to a forthcoming publication, as it is outside the scope of this paper.

4.3 *ROT is currently not a reliable parameter in the AIS feed*

The main drawback lies in the fact that very often the rate of turn indicator is not connected with the AIS transponder, although according to SOLAS Section V Reg 19, (2.9) "All ships of 50 000 gross tonnage and upwards shall, ... have: (2.9.1) a rate of turn indicator, or other means, to determine and display the rate of turn; and (2.9.2) a speed and distance measuring device, or other means, to indicate speed and distance over the ground. ... If a ship is equipped with an AIS system and a rate of turn indicator, then the ... . Rate of Turn values are hold in the corresponding AIS data field." Unfortunately, the majority of ships in the database from the Norwegian Coastal Authority do not log (or transmit correctly) their rate of turn in the AIS signal. From roughly 16 000 ships in our dataset, only 6.5 % of the ships had 20 (or more) different rate of turn values, whereas the vast majority had less than just 4 different values. This is in alignment with quality assessment studies of AIS signals (Felski & Jaskolski (2012)).

4.4 *Reconstruction of ROT from other parameters*

In case of missing or bad values, the ROT and CA may in principle be reconstructed from the heading or trace and speed of the vessel, e.g. Aarsæther & Moan (2007). However, if the AIS sampling interval is too long, the ROT can no longer reliably reconstructed from the heading signal. Reconstruction tests performed showed that, due to the large inertia of vessels, any short term large ROT values are effectively smoothed out. On the other hand, the use of bow propeller or tug boats for maneuvering can result in sharp turns in the AIS traces, which are then wrongly interpreted as instances with high ROT. It is not only the lack of ROT values in the AIS feed that is challenging, but also the data quality issues when trying to reconstruct ROT or CA. Known and experienced examples are: 1) the AIS longitude and latitude values may jump several hundred meters, 2) wrong time stamps are assigned, and 3) a continuous trace will sooner or later have holes (lack of data).

5 CONCLUSION

In this paper we presented a new methodology for identifying and characterizing occurrences of non-normal maneuvers, that could be candidates for safety critical situations. The method utilizes high frequency AIS data feeds, and utilizes the usually disregarded rate of turn and speed over ground parameters. A very high ROT value may indicate an unnatural large change in the heading of the ship. Our central assumption is that most safety critical situations such as (near) collisions are almost always accompanied by some more or less successful evasive maneuvers, i.e. maneuvers with sharp turns. This approach requires the capability of handling and analyzing large amount of data. For instance, the entire data set for all vessels in Norwegian waters over a half a year, consists of roughly 3 billion AIS records.

Our study clearly demonstrates that from high resolution ROT, it is straight forward and indeed very fast to single out potential critical situations characterized by non-normal maneuvers. Knowing the place and time of the incidence, it remains to check if there were any another vessels in the vicinity by e.g. applying the zone approach. It is also important to realize that non-normal maneuvers may occur even when there are no other vessels nearby.

The examples in Figure 6 demonstrate that a significant amount of human behavior can be inferred from ROT and SOG data. Note that our methodology automatically takes into account how dangerous a situation is perceived by the navigator. The more dangerous a navigator sees an encounter, the more vigorous he will maneuver, and the logged ROT will consequently be higher. One could also study how evasive actions from ROT and SOG will relate to the shortest distance between vessels, or one may even show what actions were not taken. For instance, in our case study, it was found that the evasive maneuver started 31.7 seconds before the collision. A similar study may be performed to examine when navigators start to initiate their course adjustments to avoid critical situations. In the end, individual navigators (within a shipping company) could be benchmarked regarding how risk avert they are compared to others (i.e. ROT) and what is their comfort profile (i.e. CA and impulse).

As AIS signals are continuously received by the Vessel Traffic Stations (VTS), an occurring non-normal evasive maneuver could be detected in real time and flagged on their ECDIS (Electronic Chart Display and Information System) displays. This would of course not avoid critical situations, but it might force navigators to behave more carefully as they know that the VTS can see when and how they reacted.

The intention of this paper has been twofold; to demonstrate the value of so far disregarded parameters, e.g. ROT, in the AIS feed, and to present a new way of identifying and analyzing potential safety critical situations using ROT instead of a traditional zone concept. Our goal is to convince the reader that there are indeed other parameters in the AIS data feed that could give valuable information, other than the geo location. We believe the rate of turn is of special interest, as it almost allows looking the navigator over his shoulder, and see what he/she is doing (or not doing). We hope that our work initiates more research on safety at sea, that actually uses measurement data such as ROT in AIS. Research on human behavior in vessel maneuvering is based on different behavioral strategies such as risk prone, average risk, and neutral risk (Hoogendoorn et al. (2013)) which could actually be correlated to the rudder actions (ROT).

Our message to the IMO and national authorities is to make sure ROT is logged and transmitted correctly. The current fraction of around 5 % of the ships, properly logging ROT, is too low.

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