

and Safety of Sea Transportation

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

K. G. Aarsæther & T. Moan Norwegian University of Science and Technology, Trondheim, Norway

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 timeseries 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).

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

where T=reference image matrix and I=the test image matrix with translation (u,v). The crosscorrelation 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 timeseries 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.

$$\kappa = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\left(\dot{x}^2 + \dot{y}^2\right)^{3/2}}$$
(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 timeseries 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. Timeseries 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	Туре	Variable		Location	n Scale	Shape
1*	Turn	k.ext	[1/m]	-5.20e-4	2.75e-3	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	4 -9.34
		speed	[kn]	8.3	4.15	3.12
4 St	raight	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 to-gether 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.

REFERENCES

- Aarsæther K. G. & Moan T. 2007. Combined Maneuvering Simulations, AIS and full-mission simulations. In Adam Weintrit (ed) Advances in marine navigation and safety of sea transportation; proc 7. intern. symp. on navigation Gdynia 20-22 June 2007
- Azzalini A. 1985. A class of distributions which include the normal ones. *Scandinavian Journal of Statistics* 12:171-178
- Brown L. G. 1992. A survey of image registration techniques. ACM computing Surveys 24:325-376
- Gucma L. & Goryczko E. 2007. The implementation of oil spill cost model in the southern Baltic Sea area to assess the possible losses due to ship collisions. In Adam Weintrit (ed) Advances in marine navigation and safety of sea transportation; Proc 7. intern. symp. on navigation Gdynia 20-22 June 2007
- Hutchison, B.L.; Gray, D.L. & Mathai, T., 2003. Maneuvering simulations - an application to waterway navigability. *Transactions of the Society of Naval Architects and Marine Engineers* Vol 111:485-516
- Merrick J.R.W.; van Dorp J.R.; Blackford J.P.; Shaw G.L.; Harrald J. & Mazzuchi T.A. 2003. A traffic density analysis of proposed ferry service expansion in San Francisco Bay using a maritime simulation model. *Reliability Engineering* and System Safety. Vol 81(2):119-132
- Vetterling W.T.; Press H. P.; Teukolsky S. A.; Flannery B. P. 2007. Numerical recipes – the art of scientific computing. Cambridge university press
- Zitová B. Flusser J. 2003. Image registration methods: a survey. *Image and vision computing* 21(11):977-1000