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Dynamic 'Standing Orders' for Autonomous Navigation System by means of Machine Learning

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Abstract. Globalisation and new environmental legislations lead to a rising need for new technological developments for the shipping industry, especially creating smart ports and smart waterways. Thus, Maritime Autonomous Surface Ships (MASS) are on the horizon. In order to be able to operate safely in the presence of other vessels, a module that dynamically determines action ranges for avoidance manoeuvres based on machine learning algorithms will be developed. Using historical AIS data, which provide ship's dynamic as well as static and voyage related data, ship trajectories and thus historical encounter situations of ships are extracted. Using k-means clustering, navigational behaviour of the vessels during an encounter situation can be examined and predicted for future encounter situations.

1. Introduction
Continued increase in levels of automation and digitisation in all industry sectors constantly improves technological efficiency. Today, waterborne is the largest international transport sector with 90% of transported goods [1]. Globalisation and new environmental legislations lead to a rising need for new technological developments for the shipping industry. The global vision of Shipping 4.0 includes integrated maritime smart embedded systems with a high level of autonomy, cloud computing, big data analytics and mobile services [2], [3]. Various initiatives are driving the development of such cyber-physical systems for the shipping industry, which already exist, in the automotive, aeronautic and manufacturing industry. Their overall aim is to create smart ports and smart waterways. These high demands led to the development of Unmanned Maritime Systems (UMS) and especially Maritime Autonomous Surface Ships (MASS).

Even though the first classification rules for the autonomous operation of ships (e.g. from DNV GL [4], Lloyd’s [5] or Bureau Veritas [6]) have now been established and the IMO has also adopted the legal framework conditions for MASS, the technical ship concepts are still predominantly in the prototype stage. Prominent prototypes can be found among other things in the tug sector, where RollsRoyce/Svitzer [7] as well as Kotug [8] have their first real prototypes. In Norway, there is a commissioned fertiliser ship for the cargo ship sector, the YARA Birkeland [9], whose technology is currently under development.

These developments are driven by the core requirement of ensuring safe operation and navigation. For this purpose, collisions and groundings must be avoided, especially on the
high seas, but also harsh weather passages must be prevented or be passed stable. It is expected that MASS will have a significant impact on the safety, efficiency and sustainability of maritime transport, addressing the key societal challenges of the European Union, so that the International Maritime Organisation prepares a legal framework for this new type of ship.

In order for an autonomous navigation system to be able to operate safely, especially in the presence of other vessels, a module that dynamically determines action ranges for avoidance manoeuvres based on machine learning algorithms is developed. Using historical AIS data, which provide ship’s dynamic as well as static and voyage related data, ship trajectories and thus historical encounter situations of ships are extracted. Using k-means clustering, navigational behaviour of the vessels during an encounter situation can be examined and predicted for future encounters.

Based on an introduction to autonomous ship navigation focusing collision avoidance hazards, the algorithm for dynamic standing orders is described and validated in detail in the subsequent section 3 followed by the conclusion and outlook in the 4th section.

2. Autonomous Navigation

An initial concept for an unmanned dry bulk carrier during deep-sea voyages was developed within the EU-funded MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) project [10]. With regard to the autonomous navigation system developed within the project, ”COLREGs and safe operation in harsh weather” [10] were incorporated.

Nevertheless, in today’s view of merchant ships, navigation is still a human-oriented task. This is also reflected in the latest performance standards for integrated navigation systems by IMO MSC.252 (83) [11] representing the best state-of-the-art technology on ship bridges. In contrast to individual, separate bridge devices, certain information is already integrated to create added value. Compared to separate systems, it mainly aims at ”creating added value for the operator to plan, monitor and/or control the safety of navigation and the progress of the ship” [11]. With regard to the four process stages of control [12]:

- Information acquisition,
- Information analysis,
- Decision and action selection as well as
- Action implementation

this means that automation on board is essentially limited to the acquisition of information and, to a lesser extent, the analysis of information. In particular, the last two process steps of decision selection and implementation are in most cases carried out exclusively by human. Examples are navigation through harsh weather and avoidance of groundings and collisions.

Even for market-leading manufacturers of autopilots, the correct parameterization of systems requires human intervention and a subjective perception of environmental influences as the basis for the selection of parameters. Intelligent algorithms for determining the relevant parameters depending on current performance information of the main engine and external influences required for efficient autonomous ship operation have so far not been used in the current maritime market. A system which provides the optimal operating parameters taking into account the ship-specific characteristics and influencing factors for existing autopilots is not available on the market.

Despite some concepts for the modelling of collision avoidance according to COLREGs [13] [14] [15], perfect information is required and only certain rules of COLREG are covered. In order to model the COLREG-compliant avoidance maneuver of ships, criteria for modelling an existing risk of collision according to COLREG rule 7 are defined. In the case of an existing
achievement of the criterion can be determined, ”whether COLREG rule 13, 14, 15, 18 or 19 applies” [16].

By examining the Closest Point of Approach (CPA) and the Time to Closest Point of Approach (TCPA) defined in Section 3, a collision risk and thus a necessary avoidance manoeuvre according to the COLREG rules mentioned above should be done when the TCPA is positive (lies in the future) and the CPA from the ship to the centre of the traffic ship domain is less than the traffic ship domain radius (cf. figure 1) [16]. All ships within a predefined action range of a ship and thus a radius of \( r \in \mathbb{R}_{>0} \) nautical miles are validated and thus triggered by the developed modules.

![Figure 1. Standard encounter situation: visualization of CPA and ship domain.](image)

Nevertheless, both the distance of the CPA and the existing ship’s domain as well as the action range of the ship are entered manually and adjusted according to the sea area navigating in. Within the paper, a dynamic indication of these values is presented.

3. Dynamic Standing Orders

In order to model dynamic standing orders, it is assumed that a critical encounter exists and that an evasive manoeuvre must therefore be initiated if the distance between two ships is below the action range and at the same time the CPA is below the ship’s domain.

3.1. Data Source

The data of the Automatic Identification System (AIS), which was introduced by the IMO to increase safety in shipping, provides the data basis for the following models. The data transferred by AIS transmitters for the exchange of nautically relevant information between different vessels and shore stations can be classified in static data, dynamic and voyage-related data. For further analyses the AIS dataset for the period 01.02.2016 - 30.04.2018 of the North Sea and Baltic Sea will be used. For details regarding the AIS, it is referred to the Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band; Recommendation ITU-R M.1371-5 of the International Telecommunication Union [18].
3.2. Requirements
A ship encounter is defined as the meeting of one own ship and one traffic ship. In the standard encounter, the notation is as follows (see also figure 2 below):

- \( x \) := course over ground of own ship (as angle measured with regards to true north)
- \( y \) := course over ground of traffic ship (as angle measured with regards to true north)
- \( v \) := speed over ground of own ship (in meters per second in the direction of \( x \))
- \( w \) := speed over ground of traffic ship (in meters per second in the direction of \( y \))
- \( t \) := longitudinal distance (in meters measured from own ship to traffic ship)
- \( u \) := lateral distance (in meters measured from own ship to traffic ship)

Figure 2. Parameters used for CPA and TCPA calculation.

One of the main measures for collision avoidance assessments are the (distance at) Closest Point of Approach (CPA) as well as the Time to the Closest Point of Approach (TCPA) mentioned in section 2. The Closest Point of Approach indicates the smallest distance between the own ship and the traffic ship. Accordingly, the TCPA indicates the time difference between now and the time of reaching the CPA, so that it can assume both positive and also negative values. Hereby, positive values mean that the CPA has not occurred yet, while negative values mean that it occurred in the past and the vessels are already sailing apart. Given the equation of motion for the own ship as well as the traffic ship, the actual distance between those with respect to time can be calculated based on the following formula:

\[
\left| \begin{pmatrix} t \\ u \end{pmatrix} + \tau \cdot w \cdot \begin{pmatrix} \sin y \\ \cos y \end{pmatrix} - \tau \cdot v \cdot \begin{pmatrix} \sin x \\ \cos x \end{pmatrix} \right| \quad (1)
\]

Since the CPA is defined as the minimum distance, the formula is derived with respect to time \( \tau \) and the corresponding null’s of the derivate must be found:

\[
\frac{d}{d\tau} \left| \begin{pmatrix} t \\ u \end{pmatrix} + \tau \times w \times \begin{pmatrix} \sin y \\ \cos y \end{pmatrix} - \tau \times v \times \begin{pmatrix} \sin x \\ \cos x \end{pmatrix} \right| = 0 \quad (2)
\]
A transformation of the equation to $\tau$ results in the TCPA given in seconds from the current situation:

$$\tau_{TCPA} = \frac{t \cdot v \cdot \sin x - t \cdot w \cdot \sin y + u \cdot v \cdot \cos x - u \cdot w \cdot \cos y}{v^2 + w^2 - 2 \cdot v \cdot w \cdot (\sin x \cdot \sin y + \cos x \cdot \cos y)} \quad (3)$$

The TCPA can be entered in equation (1) to calculate the distance assuming constant speed and course:

$$\left| \left( \frac{t}{u} \right) + \tau_{TCPA} \cdot w \cdot \left( \frac{\sin y}{\cos y} \right) - \tau_{TCPA} \cdot v \cdot \left( \frac{\sin x}{\cos x} \right) \right| \quad (4)$$

This results in the following equation for the CPA given in meters:

$$CPA = \sqrt{\frac{(u \cdot v \cdot \sin y - t \cdot w \cdot \cos y - u \cdot v \cdot \sin x + t \cdot v \cdot \cos x)^2}{v^2 + w^2 - 2 \cdot v \cdot w \cdot (\sin x \cdot \sin y + \cos x \cdot \cos y)}} \quad (5)$$

### 3.3. Ship Domains

The ship domains indicate the area around a ship, which should be kept free from other ships at all times if possible. Figure 3 depicts the Fujiu ship domains with main and secondary axes in relation to length and breadth, based on [17]. Since the ship domains are defined as a function of the ship’s length and breadth, the ship domains of AIS data are determined using the center distance true azimuth projection as a projection of the ship’s position with the ship’s position as the center.

![Figure 3. Ship domains based on Fujiu with main and secondary axes in relation to length and breadth [17].](image)

### 3.4. Approach: Iterative k-Means

To determine dynamic standing orders of ships, the first step is to examine, if ships have encountered. The AIS data defined in section 3.2.1 and in particular the latitude $\varphi \in [-90^\circ, 90^\circ]$, longitude $\lambda \in [-180^\circ, 180^\circ]$ as well as the timestamp $t$ and corresponding speed $v$ and course $x$ over ground are considered. Using the folium [19] module of Python [20], trajectories of
ships can be determined at certain points in time and thus encounter situations examined using intersections of these trajectories.

By using a dataset limited in place (and thus latitude, longitude) and time, in a subsequent step dynamic and real-time capable trips are displayed, which summarize the waypoints of a voyage of a ship and thus reflect the motion behaviour of a ship over time during an possible encounter or avoidance maneuver. To get the trips, lists of uniform MMSIs ("Maritime Mobile Service Identity") representing the ship id will be created. Based on this, a trip is created for each ship that has crossed the previously defined location in the previously defined time. The first appearance of the ship is selected as the starting point and subsequent waypoints are sequenced. Relying on the assumption that the available data have a distance of one AIS message per minute, a new trip is created if messages have a gap of more than 30 minutes.

Given the equations (3) and (5), the CPA and TCPA of the different trips are calculated. In addition, the collision type (crossing, overtaking, head-on, undefined) according to COLREG is determined with the help of the relative bearing of the ships. Based on the assumption that an encounter situation may exist when ships approach each other closer than $20\text{NM}$, the distances and CPAs of these are determined for each point in time.

Figure 4 shows the distances of two ships depending on the DCPA values and the selected ship domain from one nautical mile for a subsample. In addition, the predefined action of $6\text{NM}$ and ship domain of $1\text{NM}$ are depicted, so that only a very small area of critical situations is displayed.

Since no labelled data is available, an iterative k-means [24] algorithm is used to model proposed intervals for ship domains and action ranges. This is due to the fact that the data points are fairly uniformly distributed as shown in Figure 4. As a result, even a normal kMeans algorithm will tend to distribute the points horizontally and vertically. To avoid this fact, k-means clustering is repeated iteratively by forming $n \in \mathbb{N}$ clusters within a first step. Based on these clusters, the most dangerous quarter is selected and again k-means is applied to this in order to create $n \in \mathbb{N}$ clusters again excluding non-critical situations in two further steps. From the generated clusters, the cluster with the most critical value on average is selected, with which corresponding intervals for the action ranges and ship domains can be specified.

For modelling the cluster, the input parameters of the current distance $d$, distance to CPA $\text{CPA}$ and a scaling factor for the assessment of critical encounters $\gamma \in \mathbb{R}_{>0}$ are used with $\gamma$ being 0 if $\text{cpa} < 1$ and $d < 6$ or a randomized value between 60 and 300 if not. Based on the selected critical cluster $c$, the intervals of the action ranges $A$ and ship domains $S$ are defined using the average $\mu$ and standard deviation $\sigma$:

$$A = [\mu(d_c) - \sigma(d_c), \mu(d_c) + \sigma(d_c)]$$
and

\[ S = [\mu(CPA_c) - \sigma(CPA_c), \mu(CPA_c) + \sigma(CPA_c)] \quad (7) \]

The number of clusters is iteratively determined by performing k-means clustering for \( n = 5, \ldots, 20 \in \mathbb{N} \) and determining the silhouette coefficient to examine the fit of the model to the data \([22]\) \([23]\).

3.5. Validation

Figure 5 depicts a subset of the representative data after using k-means with \( n = 4 \) clusters. The second and third cluster step with \( n = 4 \) and \( n = 3 \) clusters are presented in Figure 6 and 7. It can be seen that the amount of data is significantly reduced, so that after the second step 6% of the initial data is available and after the third one less than 1%. In addition, it is evident that the data are limited to almost critical situations.

![Figure 5. Scatterplot of DCPA and distance for a subsample after the first clustering.](image)

![Figure 6. Scatterplot of DCPA and distance for a subsample after the second clustering.](image)

![Figure 7. Scatterplot of DCPA and distance for a subsample after the third clustering.](image)

After the third iteration, the amount of data is limited to critical situations whose action ranges and ship domains are specified by the following intervals:
\[ A = [1.32, 5.25] \] (8)

and

\[ S = [0.31, 1.15] \] (9)

Hence, it can be stated that manually set ship domains of 1NM and especially action ranges of 6NM are often set too high and avoidance manoeuvres can be dynamically initiated at a later point in time and thus a much smaller distance, without suffering from collisions.

4. Conclusion and Outlook

This paper has presented an iterative k-means concept for examining dynamic standing orders of vessels regarding collision avoidance. From the first internal tests it can be concluded that action ranges of ships and thus standing orders can be dynamically adapted than having to be defined manually before the start of a working shift for a predefined sea area. This includes the various encounter situations of ships as well as ships considered in a differentiated way. The approach chosen also makes it possible to determine action values specific to the sea area.

The inclusion of weather or sea chart data could further increase the accuracy of the algorithm and increase the safety of maritime traffic on the way to more automated navigation. Nevertheless, the certification of machine learning algorithms and the real-time capability of the calculations, which has not yet been clarified, must be taken into account and further investigated in this context.

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