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SNAT: SIMULATION–BASED SEARCH FOR NAVIGATION SAFETY. THE CASE OF SINGAPORE STRAIT

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ABSTRACT

As the bottleneck of the shipping routes from the Indian Ocean to the Pacific Ocean, the Singapore Strait is handling high daily traffic volume. In order to enhance navigational safety and reduce collisions at sea, several approaches have been proposed. However, most of the contributions adopt deterministic algorithms, failing to consider the stochasticity due to human behaviors of ship captains. Moreover, the effectiveness of these approaches is hindered by the fact that their focus is on providing a globally optimal safe set of trajectories to all vessels involved in encounter situations, almost neglecting each captain's perspective. We propose Safe Navigation Assistance Tool (SNAT), a simulation–based search algorithm to assist the captain by suggesting highly safe and robust maneuver strategies for conflict avoidance. Extensive numerical experimentation were performed proving the effectiveness of SNAT in reducing the number of conflicts, with respect to real data provided by the Automatic Identification System (AIS).

1 INTRODUCTION

The Singapore Strait is a 105-kilometer long, 16-kilometer wide corridor connecting the Strait of Malacca and the South China Sea (Figure 1). As one of the busiest straits in the world, it is crossed by about 400 vessels at any one time (MPA 2013). Hence, navigational safety is a fundamental aspect to consider. The International Maritime Organization (IMO), the main regulatory body for sea traffic management, has proposed the International Regulations for Preventing Collisions at Sea (Colregs). Colregs regulates maneuver strategies with the scope to decrease the accident occurrence.

With compliance to Colregs and other economic criteria, good marine practice for taking maneuvers should fulfill the following: (1) the course alteration should be bounded between 15 degrees and 60 degrees, since the course alterations less than 15 degrees might be misleading for navigational systems (and therefore may lead to collisions) and course alterations larger than 60 degrees are not recommended for efficiency reasons; (2) maneuvers to starboard (right) side should be favored over maneuvers to port (left) side; (3) speed alterations should be performed only in case no alternative strategy exists to avoid conflicts; (4) speed decrease should be preferred to speed increase; (5) extreme changes in speed should not be performed.

Nonetheless, given the remarkable environmental and operational costs both the marine authorities and ship companies incur due to marine accidents and safety violations, a considerable effort has been dedicated to the improvement of the available technologies for tracking vessels in crowded sea regions as well as to the development of effective models and methods to support the

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land offices and vessel captains predicting and avoiding conflict situations. The Automatic Identification System (AIS) provides real–time data through VHF (Very High Frequency) signals, which include vessel name, length, weight, speed and course. With this technology, a wide range of software tools have been developed to provide navigational guidance based upon AIS data.

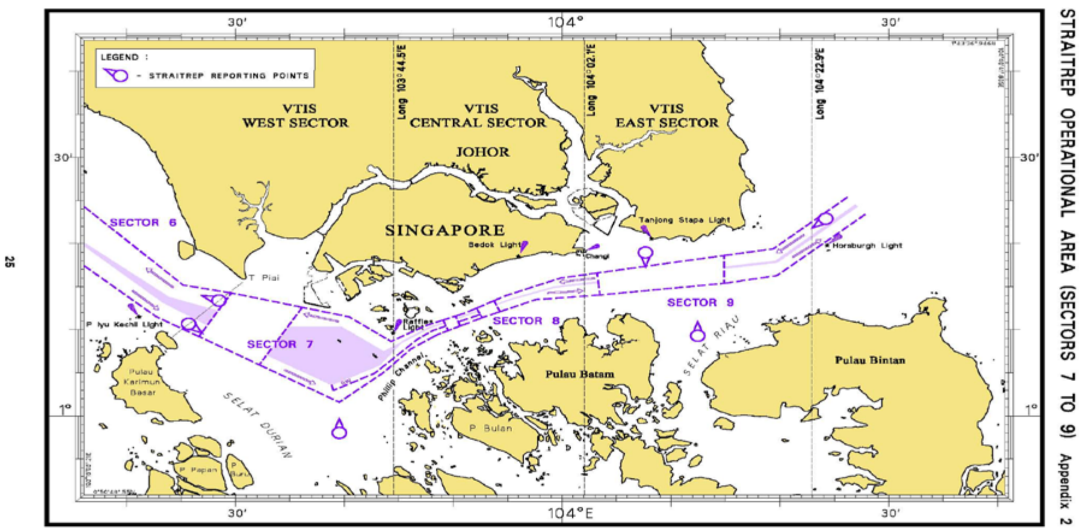

Figure 1 : Map of the Singapore Strait.

However, despite the tremendous efforts of the Maritime and Port Authority (MPA) of Singapore to monitor traffic at the Singapore Strait and the noticeable technological advancement, the conflict rate is still high. According to Weng et al. (2012), the average number of conflicts occurring at the Singapore Strait is about 2000 per month. Among the conflicts, some are indeed severe accidents such as the recent collision between two bulk carriers in the Singapore Strait on Feb 10 (2014) which was the third collision in 13 days; resulting in a total of 680 metric tons of fuel being spilled (The Straits Times, 2014). Nonetheless, less severe conflicts must be the focus of any support system in order to avoid much worse situations.

Although many contributions can be found in the area of conflict avoidance in multi-ship encounter situations, most of them adopt deterministic approaches which do not take into consideration the stochasticity of ship movements due to the unpredictable behavior of the ship captain.

This work proposes a simulation–based search algorithm named Safe Navigation Assistance Tool (SNAT) which, installed on a vessel, pursues the objective to effectively reduce conflicts under stochastic scenarios determined by the random behaviors of the vessel captain and of the surrounding vessels. In particular, SNAT was developed with the scope of being integrated with the on board navigation support devices.

The remainder of the paper is structured as follows: section 2 presents the problem that we want to address through this study, followed by section 3 which is the proposed methodology. Experimental conditions and results are explained in section 4. Section 5 concludes the paper and provides directions for future research.

2 EXISTING APPROACHES AND CONTRIBUTION

Navigation safety algorithms seek a set of optimal maneuver (usually referred to as *maneuver strategy*) which avoids possible conflict situations while minimizing a defined utility function. The maneuver strategies proposed to ship captains can consist of a course change, speed change or a combination of both. A course change can be either a positive change to the right or a negative change to the left, while a speed change can be either a decrease or an increase in the vessel velocity.

Two main approaches can be individuated in the literature related to planning optimal ship trajectories in encounter situations: (1) deterministic approaches based on differential games (Lisowski 2007); (2) heuristic approaches with the application of evolutionary algorithms (Michalewicz et al. 2000).

The former model multi-ship encounter situations as a dynamic game with each vessel as a player having its own maneuver strategies. This approach captures the dynamic interaction between vessels. Indeed, when one vessel changes its maneuver strategy other vessels react accordingly. However, high computational complexity is its major drawback.

The latter family of approaches uses mechanisms such as reproduction, mutation and recombination to generate candidate maneuver strategies and it finds the optimal set of ship trajectories according to a given fitness function. However, the optimal trajectory for each ship is found based on pre-determined trajectories of other ships, i.e., other ships' motion parameters are assumed to be constant and this assumption can lead to large biases. Despite this shortfall, while most studies do not consider Colregs, the most recent contributions in this family take Colregs into consideration while searching for the strategy to suggest.

The optimal solution generated by these two families of approaches is represented by the set of safe trajectories for *all* ships in the domain considered by the search procedures (i.e., the *monitored area*). In fact, most of current studies focus on methodologies that provide a *globally* optimal safe set of trajectories for all vessels in the monitored area, i.e., the optimality is defined with respect to a global utility. However, little attention is directed towards examining random human behaviors and their impact on the effectiveness of the developed procedure. Nonetheless, random behavior is a fundamental aspect to consider as it reflects the preference of the ship captain for choosing a maneuver strategy maximizing its own utility which might differ from the global utility considered by the mentioned algorithms. In fact, it is very likely for ship captains to choose their own preferred maneuver strategies, which may undermine the effectiveness of safe trajectories proposed by current approaches.

The method proposed in this paper, as the recent evolutionary studies, considers Colregs regulations, i.e., it suggests to the vessel having SNAT in place, whenever possible, a set of optimal maneuvers which are also Colregs compliant.

SNAT has two further distinguishing features with respect to the main analyzed algorithms: (1) it considers the random vessels moves as well as the stochasticity due to the human behavior of ship captains, and (2) simulation is actively integrated with the search algorithm. In particular, as will be detailed in section 3.2, each candidate strategy is tested against several simulation replications enabling the evaluation of the strategy safety level leading, eventually, to the search of further solutions. This aspect of the proposed procedure is relevant since it characterizes both the safety level of the generated solution and its robustness with respect to different future scenarios.

3 SNAT OVERVIEW

SNAT is an integrated simulation search algorithm that suggests optimal maneuvers required for an individual vessel (referred to as *own vessel* in the rest of the study) to avoid conflicts with surrounding vessels (referred to as *target vessels* in the rest of the study). Specifically, a search algorithm generates candidate maneuvers and interacts with a discrete time simulator which emulates the vessel's dynamics and evaluates the quality of the proposed solution. Being at its first implementation, SNAT was not installed on board yet. Hence, we integrated the SNAT algorithm into a simulation–based evaluation procedure, in order to provide an estimate of its effectiveness in decreasing the number of conflicts when in place. In the evaluation procedure simulation replaces the real world emulating future positions of own and target vessels. Section 3.1. illustrates the main assumptions underlying the SNAT simulation optimization algorithm, and section 3.2 describes the SNAT steps with more detail. Finally, the evaluation procedure is described in section 3.3.

3.1 Model Assumptions

SNAT recognizes conflict situations using the concept of *ship domain* defined as the surrounding effective area that the ship captain wants to keep clear of other ships or fixed objects (Goodwin 1975). Several regular shapes are adopted in the literature to model the domain: Goldwell (1982) consider an ellipse, whereas Wang et al. (2009) propose an eclipse with semi-minor axis equal to 1.6 times the length of the vessel and semi-major axis which is 4 times the length of the vessel. The use of ship domain enables *conflict avoidance* on top of *collision avoidance*, as the ship domain violation (conflict) occurs before the contact between two vessels (collision).

The ship domain shape adopted in this study is the *circular domain shape* with a radius equal to 4 times the length of the vessel and a conflict is detected if the straight-line distance between own vessel and the target vessels is less than the radius of the shape. This choice leads to the detection of potential conflicts that may not be captured if an eclipse ship domain is used and take precautions accordingly.

When potential conflicts are detected, the probability that ship captains will take immediate maneuvers, referred to as P_M, is assumed inversely proportional to the time to earliest conflict or, in navigational terms, *time to closest point of approach* (referred to as TCPA in the rest of the paper). More specifically, we assume ship captains will perform immediate maneuver if the conflict detected is within a defined threshold interval of 10 minutes (i.e., $P_M = 1.00$ in case $TCPA \leq 10$ as it is shown in Table 1). If the time to the detected conflict is larger than this threshold, the probabilities that ship captains will take immediate maneuvers were set according to expert opinion. In particular, three scenarios were designed as shown in Table 1. Scenario 1 refers to the *optimistic* case in which the ship captain performs immediate maneuvers, according to SNAT suggestion, 80% of the times if the TCPA is between 10 and 20 minutes and 60% if TCPA is between 20 and 30 minutes. Scenario 2 represents the situation in which the ship captain performs immediate maneuvers 75% of the times if the TCPA is between 10 and 20 minutes and 55% if TCPA is between 20 and 30 minutes. Finally, in scenario 3, the ship captain performs immediate maneuvers 70% of the times if the TCPA is between 10 and 20 minutes and 50% if TCPA is between 20 and 30 minutes.

Table 1 : P_M values.

Probability	**Scenario 1**	**Scenario 2**	**Scenario 3**
$P_M \mid TCPA \leq 10\ min$	1.00	1.00	1.00
$P_M \mid 10\ min < TCPA \leq\ 20\ min$	0.80	0.75	0.70
$P_M \mid 20\ min < TCPA \leq 30$	0.60	0.55	0.50

We model the unpredictable maneuver that the ship captain performs due to its individual preferences through the *probability of a deliberate* change in course and/or speed computed according to the estimated distribution of the change in course/speed. Herein, *deliberate* refers to a voluntary maneuver characterized by a change in either speed or course at least 1.5 standard deviations away from average changes estimated for each vessel. The considered reference value was chosen because minor deviations may be due to external factors such as wind, water flow and sensitivity of AIS receivers.

We distinguished the following *random maneuver*: (A) change in course associated with probability $P_C = 0.37$, (A.1) change in course with right turn associated with a probability $P_R | P_C = 0.49$, (A.2) change in course with left turn associated with a probability $P_L | P_C = 0.51$, (B) change in speed associated with probability $P_S = 0.12$, (B.1) decrease in speed with associated probability $P_D | P_S = 0.73$, and (B.2) speed increase with associated with a probability $P_I | P_S = 0.27$.

In order to estimate the aforementioned probabilities, the AIS data for 1640 vessels over a 48–hours period at the Singapore Strait were collected summing up to over 250,000 records. The traced positions were used to evaluate the changes in course and speed between two consecutive AIS updates. In order to define a distribution for each of the aforementioned four maneuvers, the data were tested against 15 distributions at 5% significance level and distributions with the highest goodness of fit were selected. In particular, distributions for degree of course change to the right, degree of course change to the left and percentage of speed decrease were assigned a normal distribution, while the test for the distribution of percentage of speed increase suggested a lognormal fit. Parameters identified for all maneuver options are summarized in Table 2; all the values are computed with respect to the average changes estimated from the AIS data.

Table 2: Distributions for different maneuver options.

Maneuver Option	**Best-fit Distribution**	μ	σ	**Unit Measure**
Turn Right	Normal	103.05195	46.42626	[°]
Turn Left	Normal	-98.53705	45.74620	[°]
Decrease Speed	Normal	-0.57881	0.19179	[knots]
Increase Speed	Lognormal	0.47164	0.28727	[knots]

3.2 SNAT Detailed Procedure

As outlined in Figure 2, once installed on the vessel, SNAT will receive AIS data collection in case of conflict detection. At this point the SNAT procedure starts with the following steps: (1) *Maneuver Strategy Generation Procedure*: if a conflict is detected, the optimization algorithm seeks the best maneuver minimizing a utility function which is based on the Colregs best practices; (2) *Maneuver Evaluation Procedure*: the probability of future conflicts given the candidate maneuver strategy is estimated through several simulation replications. In case the probability of conflict is below a predefined threshold level SNAT returns the solution to the on–board devices and it will be run again at the next detected conflict.

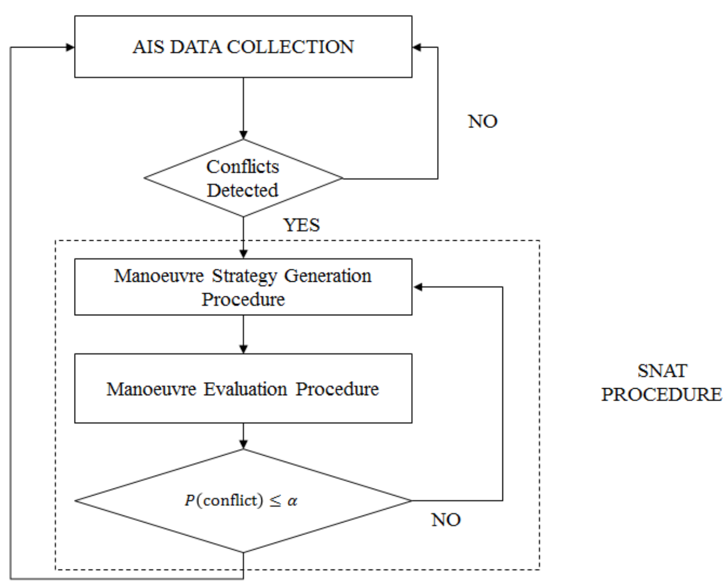

Figure 2 : SNAT algorithm overview.

When a conflict is detected, SNAT searches for optimal changes in course $\Delta C_{R,t}$ (right turn) or $\Delta C_{L,t}$ (left turn) and change in speed $\Delta S_{D,t}$ (speed decrease) or $\Delta S_{I,t}$(speed increase) such that the own vessel can avoid potential conflicts. One of the features of SNAT is that it explicitly considers Colregs regulations, i.e., whenever possible, the algorithm proposes as optimal strategy a set of maneuvers which are Colregs compliant (Table 3).

Table 3: Search preference for maneuvers according to Colregs.

Preference	**Maneuver Strategy**
Rank 1	$\Delta C_{R,t}$: from $15°$ to $60°$
Rank 2	$\Delta C_{L,t}$: from $-15°$ to $-60°$
Rank 3	$\Delta C_{R,t}$: from $15°$ to $60°$ and $\Delta S_{D,t}$: from-2 knots to-10 knots
Rank 4	$\Delta C_{L,t}$: from $-15°$ to $-60°$ and $\Delta S_{D,t}$: from-2 knots to-10
Rank 5	$\Delta C_{R,t}$: from $15°$ to $60°$ and $\Delta S_{I,t}$: from 2 knots to 10 knots
Rank 6	$\Delta C_{L,t}$: from $-15°$ to $-60°$ and $\Delta S_{I,t}$: from 2 knots to 10 knots
Rank 7	$\Delta S_{D,t}$: from -2 knots to -10 knots
Rank 8	$\Delta S_{I,t}$: from 2 knots to 10 knots

The objective function guiding the search is formulated as:

$$Min\ z = \left(\Delta C_{R,t} - F_{R,L}\Delta C_{L,t}\right) + F_{C,S}\left(F_{D,I}\Delta S_{I,t} - \Delta S_{D,t}\right), \tag{1}$$

where $F_{R,L}$ is the preference factor of a right turn over a left turn; $F_{D,I}$ is the preference factor of speed decrease over a speed increase; and $F_{C,S}$ is the preference factor of a course change over a speed change. While minimizing the degree of change, the suggested maneuver strategies should avoid all conflicts in a time interval shorter than CT_{max} defined as the maximum between the TCPA related to the detected conflict and a fixed safety time factor which is an input parameter. This value determines the safety interval from current time.

The choice of the objective function is in line with the IMO considerations (best practices in section 1) and the maneuver strategies suggested comply whenever possible with Colregs according to the strategy ranking shown in Table 3. In fact, function (1) leads to (a) the minimization of the required change in course $\Delta C_{R,t}$ ($\Delta C_{L,t}$) and speed $\Delta S_{D,t}$ ($\Delta S_{I,t}$) at each discrete time step *t*, (b) the avoidance of the earliest conflict detected, and (c) it ensures there are no conflicts in the time interval CT_{max}.

Maneuver Strategy Generation Procedure

The algorithm first checks for strategies with higher rank (where the rank is defined with respect to the objective function value, Table 3). SNAT starts searching for a course change to the right from 15° to 60° with a 1° increment at each iteration in case the maneuver is detected as infeasible (i.e., it does not avoid conflict). If all Rank 1 maneuver strategies fail, SNAT proceeds to strategies with lower rank. Since the preferred strategies will always be examined first, the first feasible maneuver strategy found by SNAT is also the optimal strategy. In the worst case scenario, if all higher rank strategies are not feasible, and the least favored strategy of increasing speed by 10 knots is the optimal solution, the total number of iterations that need to be performed results as follows:

$$I_w = \sum_{i=1}^{8} I^{ri} = 46 + 46 + 46 \times 9 + 46 \times 9 + 46 \times 9 + 46 \times 9 + 9 + 9 = 1766,$$

where I_w stands for number of iterations in the worst case scenario and I^{ri} stands for the number of iterations in rank *i*.

In situations where no feasible solutions can be found in the search space of 1766 solutions, SNAT will perform the following analysis.

First, SNAT will check the TCPA related to the detected conflicts.

If TCPA is found to be greater than 20 minutes, maneuvers will be postponed to subsequent time steps, i.e., when TCPA becomes smaller. The 20 minutes threshold was set because, from pilot experiments, about 80% of conflicts detected when SNAT is not in use have TCPAs less than or equal to 20 minutes. Hence, SNAT should avoid conflicts with TCPAs less than or equal to 20 minutes since they occur more often, while for conflicts with TCPAs greater than 20 minutes a delay in maneuver is still acceptable.

When TCPA is shorter than 20 minutes and no feasible solutions can be found given the current search space, the search space will be *expanded* to allow course changes between 15 and 70 degrees and speed changes between 2 and 15 knots. The expanded search space will then consist of 3276 solutions:

$$I_E = \sum_{i=1}^{8} I^{riE} = 56 + 56 + 56 \times 14 + 56 \times 14 + 56 \times 14 + 56 \times 14 + 14 + 14 = 3276,$$

where I_E is the number of iterations in the expanded search space, and I^{riE} is the number of strategies in the expanded rank i.

Maneuver Evaluation Procedure

In order to evaluate the *feasibility* of the maneuver, at each generated solution, *N* simulation replications are used to estimate the probability of conflict. These simulations have a maximum length of $\mathrm{CT_{max}}$ and the candidate solution *is not generating conflicts* with respect to the *i*-th replication if the straight-line distance between own vessel and all target vessels is greater than the safety distance for the next $\mathrm{CT_{max}} = 20$ minutes. In order to provide safer maneuvers under stochastic scenarios, a conservative approach was adopted while evaluating candidate strategies. In particular, the safety distance used by the evaluation procedure is variable: the initial safety distance is set to be 5.5 times the length of vessel (instead of 4 as stated in section 3.1). If the criterion is too stringent for any feasible strategy to be found, lower safety factors of 5.0, 4.5 and 4.0 are used subsequently. To decrease the required computational time, if a conflict is detected before $\mathrm{CT_{max}}$, the simulation is terminated and SNAT records a *failure* for that replication.

Once the replications have been performed, a maneuver strategy is declared *feasible* if it can avoid conflicts (failures) with all target vessels in future time $\mathrm{CT_{max}}$ with some defined probability $(1-\alpha)\%$. The candidate strategy is then evaluated in terms of the % ratio between the number of replications with zero conflicts over total number of replications (*N*). In case the effectiveness is smaller than the value $(1-\alpha)\%$, the proposed strategy is declared *infeasible* and the generation procedure is restarted. In case, given the reduced safety time and expanded search space, no feasible solution can be found, SNAT will not suggest any maneuver and it will give advice of the probability of conflict ($\beta \geq (1-\alpha)\%$).

SNAT Evaluation Procedure

In order to evaluate its effectiveness, SNAT algorithm was integrated into a simulation–based evaluation procedure as the one represented in Figure 3.

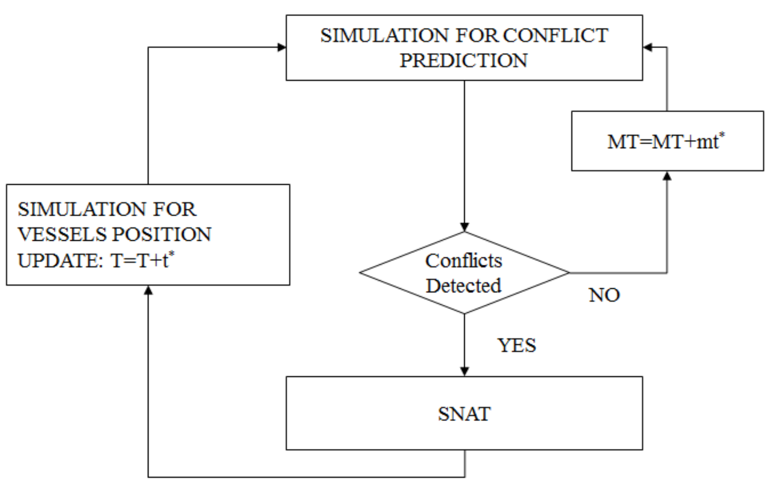

Figure 3: SNAT Evaluation Procedure.

At every step of the evaluation procedure (Figure 3), the current simulation time (replacing the real–time when AIS data are received), is referred to as T. At every time T, the *own vessel* position is generated and potential conflicts are searched up to a future time (monitor time) of $\mathrm{MT_{max}}$. The safety distance used to detect conflicts is set to be 4 times the length of the own vessel (section 3.1). To predict conflicts, the simulation advances on the *monitoring time clock* MT (while the simulation time stays at *T*) for $T \leq MT \leq \mathrm{MT_{max}}$ using a time step equal to mt^*.

In case conflicts are detected, the SNAT procedure starts.

Once the maneuver has been generated, the simulation is used to update the position of the *own vessel* accordingly. In particular, a change is made according to the solution proposed by SNAT only if the ship captain decides to take immediate action, otherwise they remain unchanged. The update procedure is different for *target vessels* whose parameters are updated according to probabilities and distributions of random vessel behaviors reported in section 3.1 (Table 2).

The updated course and speed for own vessel $\mathrm{C_{*,t}}$ and $\mathrm{S_{*,t}}$and for target vessels $\mathrm{C_{j,t}}$ and $\mathrm{S_{j,t}}$ ($j = 1, \dots, J$) are returned to the simulator to calculate updated longitude and latitude of vessels at simulation time T, i.e., $\mathrm{X_{*,T}}, \mathrm{Y_{*T}}, \mathrm{X_{j,T}}, \mathrm{Y_{j,T}}$, respectively. The same quantities $\mathrm{X_{*,MT}}, \mathrm{Y_{*,MT}}, \mathrm{X_{j,MT}}, \mathrm{Y_{j,MT}}$ are computed at monitor time MT for future conflict detection.

At this point, time T is incremented with a fixed step t^* emulating the frequency at which AIS data are received.

The simulation considers ship captains' reaction to conflicts detected as well as their tendency to take maneuvers under normal circumstances (i.e., when there are no conflicts) introducing further randomness. In particular, in *potential conflict situations*, after the earliest conflict is detected and the ship captain is about to implement the maneuver, the actual movement is affected by a random variable. More specifically, when a conflict is detected, SNAT will check whether its TCPA reaches the threshold of 10 minutes, if the TCPA is less than or equal to 10 min, SNAT assumes the ship captain will accept maneuvers suggested and take immediate actions and will update the position accordingly. However, if the threshold is not reached, SNAT will update the position according to the scenarios in Table 1. In case no actions are taken by the captain SNAT will re-compute maneuver strategies at the next time step. Also the random behaviors of target vessels in *normal circumstances* were included according to identified probabilities and distributions presented in Table 2 in order to generate the next vessel position.

4 NUMERICAL RESULTS

Experiments were conducted to test the effectiveness of SNAT in conflict avoidance under stochastic scenarios. Section 4.1 reports the detailed parameter settings for the experimental conditions, while the obtained results to evaluate the effectiveness of the approach are shown in section 4.2. In all experiments, real AIS data received from the Singapore Strait from longitude 102° to 105° and latitude 1° to 2° over 48 hours were used to set the initial vessels locations.

4.1 Parameters setting

The simulation duration was set to be 3 hours, i.e., the average time a vessel spends in regions of the Singapore Strait controlled by Singapore Vessel Traffic Service (VTS). Part of the simulation control parameters were determined from pilot experiments to trade-off between computational complexity and efficiency. Different experimental conditions were obtained separating the AIS data stream into 16 sub-streams each of 3hrs duration. In fact, because of the average stay duration in the strait is 3hrs, the subsequent streams were considered independent. The 16 data sets contain vessel information such as name, length, position, speed and course which will be used to set initial vessel parameters at the start of each simulation run. Each data set is used for 1 simulation experiment resulting in a total of 16 experimental conditions each defined by a different initial condition (i.e., relative position of the own vessel vs target vessels).

Concerning time increments t^* and mt^* (section 3.2), a value of 30s was set to be the reference line since it represents the average rate of data updates received from AIS receivers (Aarsather et al. 2009). However, preliminary tests on increments of 1min and 3min led us to set mt^* and $t^* = 1min$

thus balancing the computational efficiency and the miss-out rate (i.e., the ratio between the number of conflict not detected over the test runs and the total number of existing conflicts in the tests runs).

The maximum monitor time MT_{max} was set to be 30min since out of 186 conflicts detected over 16 test runs, when SNAT is not in place, 148 (i.e. about 80%) have TCPAs less than 25 minutes. Any further increase in MT_{max} to provide early warning is a waste of computational effort since the ship captain will always have to react to earlier conflicts first. The safety time CT_{max} was set to be either greater than TCPA or 15min such that maneuver strategies suggested by SNAT will ensure no conflicts are present at least in the next 15 minutes. Concerning the maneuver generation, 10 replications ($N = 10$) and a $(1-\alpha)\% = 90\%$ were used to evaluate each candidate maneuver strategy. Concerning the pilot random behavior, the probability P_M was set to the values in the scenario 3 illustrated in section 3.1 (Table 1).

4.2 Numerical results

The effectiveness of SNAT was tested against stochastic scenarios in which ship captains' reaction to conflict(s) are subject to randomness as well as motion parameters (speed and course) of target vessels are subject to random changes.

To test the effectiveness of SNAT under situations where ship captains may not take immediate reactions once a conflict is detected, 16 experimental conditions were conducted and the set of vessel parameters first captured by AIS receiver over a 3-hour period were used as initial input parameters for the simulation. From simulation results, initialization bias is observed when, at the beginning of simulation, the initial position of own vessel is too close to target vessels. In these conditions, conflicts detected within the first 5 minutes of simulation were removed when assessing the effectiveness of SNAT.

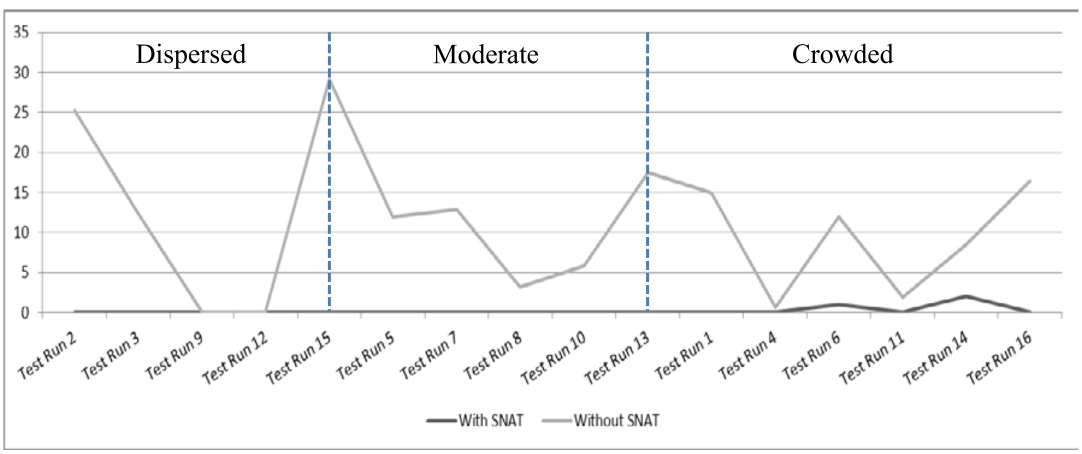

Figure 4: Average number of conflicts detected with and without SNAT.

The tests were repeated for 100 macro-replications and the average number of conflicts detected using maneuver strategies suggested by SNAT was compared with average number of conflicts detected if SNAT is not in place, as shown in Figure 4.

The 16 experimental conditions (Test Run in Figure 4) were grouped according to the initial positions of vessels obtaining three macro cases: the "Dispersed" case in which own vessel is not crowded by target vessels at the initial setting; the "Crowded" case in which own vessel is very crowded by target vessels at the initial setting; and the "Moderate" case which consists of scenarios between the two extremes.

It can be observed that, the performance of SNAT is consistent in all 16 conditions, i.e., the number of conflicts is strictly increasing as the traffic intensity increases. The same pattern cannot be recognized in the case where SNAT is not in place.

To quantify the overall effectiveness of SNAT, we computed the expected number of conflicts over 3-hour duration as $\frac{1}{16}\sum_{j=1}^{16}\frac{\sum_{i=1}^{100} C_{ij}}{100}\%$, where C_j is the number of conflicts detected under the j^{th} experimental condition under the *i-th* macro-replication. We compared this value with the number of conflicts when SNAT is not in place and computed the % improvement associated to the application of SNAT, as the the % decrease in the number of conflicts which is shown in Table 4.

We notice that the percentage reduction in the number of conflicts reaches its maximum in test Run 2 under "Dispersed" scenario, of 100.00%, whereas its minimum is in Test Run 14 under "Crowded" scenario of 76.47%.

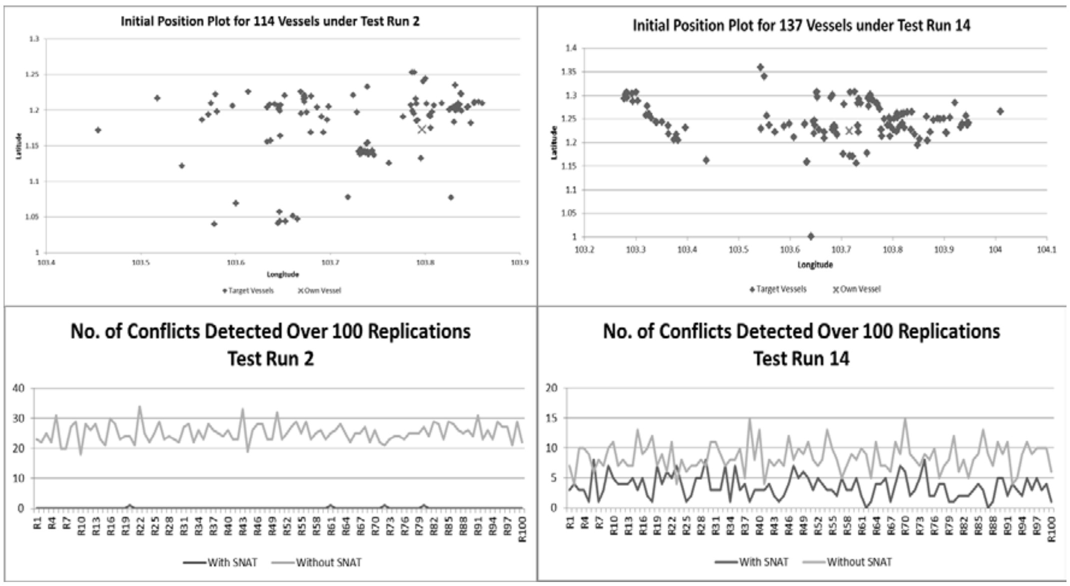

Figure 5: Effect of the initial conditions.

Table 4 : % reduction in number of conflicts in different scenarios.

Scenario	% Reduction in Conflicts
Dispersed	100.00
Moderate	100.00
Crowded	94.68

We first highlight the evidence that SNAT is never worse than the without SNAT situation. Further analysing the obtained results we observed that SNAT is sensitive to the initial conditions. Figure 5 shows the initial positions of own vessel (cross mark) and target vessel (diamond marks) for condition 2 and condition 14, as well as the respective performance of SNAT.

As it can be observed, many conflicts cannot be avoided in test run 14. This, however, is due to the fact that the vessels is starting off in an overcrowded region when the SNAT procedure is activated, making conflicts unavoidable (refer to the top right panel in Figure 5).

5 CONCLUSIONS

Navigation safety is becoming a major concern for the maritime authorities. Current approaches are not sufficient in guaranteeing conflicts avoidance as they do not consider randomness. Moreover, the available regulations to control the ship captain's maneuver proposed by the maritime authorities are usually neglected. The method proposed in this research tries to fill this gap. SNAT is a stochastic simulation–based search algorithm which provides robust optimal maneuver strategies to minimize conflict situations. Numerical results show that the effectiveness of the proposed solution varies based on the number of vessels involved in the encounter situation and their initial relative positions. However, the effectiveness of SNAT is proven remarkable under all the considered conditions.

Several extensions are under investigation. Within the scope of this study, the maneuvers taken by ship captains are assumed to take immediate effect. However, in real settings, the effective reaction time of vessels may depend on several factors such as the type of vessel, its length, weight and speed as well as human reaction time of ship captains.

Further improvements can be made by updating vessel information based on real-time AIS data. Trace-driven simulation can then be adopted to further improve effectiveness under stochastic scenarios by capturing real–time motion parameters of target vessels and develop optimal maneuver strategies based on real-time data instead of modelling the random behavior as a stochastic variable.

Moreover, especially in light of the possible integration of SNAT with the guidance support devices on board, the computational efficiency becomes a key issue. The need of running simulations to evaluate the robustness leads to the requirement of reducing the evaluation time. Furthermore, the computational effort required by the actual search procedure has to be remarkably reduced. Metamodels replacing the simulation as well as more efficient search algorithms are under investigation.

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