Automatically generating collision scenarios for testing ship collision avoidance system using sampling techniques

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ABSTRACT

We live in an era when autonomous systems are being designed and introduced in the maritime industry. A critical system on the autonomous ships is the collision avoidance system, which is responsible for safe vessel navigation. There is a great challenge in identifying encountering scenarios which could be fed for testing the collision avoidance system and ensuring situational coverage. The aim of this paper is to propose an automatic way for developing hazardous scenarios for testing the ship collision avoidance system. In the suggested methodology sampling techniques are used to develop encountering situations. Then geometrical risk metrics are used to determine whether the condition is hazardous or not. The effectiveness of the approach is investigated using a number of sampling techniques. The results demonstrate that the Sobol quasi-random sequence have more robust results in identifying scenarios, and effectiveness comparative with the Latin hypercube and random sampling Based on the findings suggestions for further enhancement and automatic development of testing scenarios are provided.

KEYWORDS

Autonomous ships, Testing scenarios, Collision, Sampling techniques

1 Introduction

We live in an era, when novel systems are being introduced, including marine autonomous surface ships (MASS) [1]. The collision avoidance system can be considered as a critical system on MASS [2]. An important challenge with collision avoidance system is identifying the scenarios that need to be tested in a simulator or during sea trials.

The navigation of ships is primarily regulated by COLREGs [3]. However, the COLREG requirements have been designed having crew in mind and not the MASS. COLREGs do not provide numerical criteria for MASS actions and their implementation rely on the crew judgement, so it can't be used to develop the testing scenarios. Several previous works have suggested the development of collision avoidance system on MASS e.g. [4-7], but very few focused on the testing and testing scenarios generation [8, 9].

The present study aims at developing testing scenarios for MASS collision avoidance system. A number of sampling techniques is employed to generate various encountering conditions, but only the hazardous situations are selected for testing. The hazardous situations are identified using geometrical risk metrics and criteria. In the study one Own Ship (OS) and two Target Ships (TS) are considered. The ships are assumed to operate in an open ocean. More details are provided in the next sections.

2 Methodology

The methodology is presented using pseudocode in Table 1. First the input parameters are defined. Then encountering situations are generated using one of the sampling techniques: Sobol sequences (SB), random Monte Carlo (RMC) sampling or Latin hypercube (LH). For each of the encountering situation, geometric distance between the OS and TS$_i$ (D_i), time to the closest point of approach between the OS and TS$_i$ ($TCPA_i$) and distance at the closest point of approach between the OS and TS$_i$ ($DCPA_i$) are estimated as risk metrics. These risk metrics are calculated on the assumption that the vessels will not change their speed and direction (holonomic model)[7]. The equations for these metrics are provided below (eq. 1-3), where $(\boldsymbol{x}, \boldsymbol{y})$ is location for each vessel, $\boldsymbol{u}$ is velocity, $\boldsymbol{\varphi}$ is vessel velocity direction, $\mathbf{0}$ and i are used to denote OS and TS_i respectively, r relative to the OS velocity and position from [5, 8, 9]:

$$D_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2} \quad (1)$$

$$DCPA_i = \left| \frac{x_{ir}u_{iry} - y_{ir}u_{irx}}{\sqrt{{u_{irx}}^2 + {u_{iry}}^2}} \right| \quad (2)$$

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$$TCPA_i = -\frac{y_{ir}u_{iry}+x_{ir}u_{irx}}{u_{irx}^2+u_{iry}^2} \quad (3)$$

In case the risk metrics violate some of the criteria, the encountering situation is considered as critical. The analysis of criteria starts with the ship that is the closest to the OS. The criteria that are considered are as follows. Firstly, $TCPA_i > 0$, as we are not interested in the situation where the closest encounter happened in the past. Secondarily, the current distance between vessels should be equal or less than 1 nm. COLREGs do not specify any specific distance, and the 1nm has been set in line with other publications [5]. It is the distance at which it can be considered that OS should take action to avoid the collision. The third is criteria related to the safety domain. The safety domain is defined using an ellipse set (a_1, b_1) at vessel location with axis dependent on the OS length (L) and speed u_0 according to equations (4-5) [5].

$$a_1 = \begin{cases}(4-0.3(10-u_0))L, \ u_0 \le 10\ kn \\ (4+0.3(u_0-10))L, \ u_0 > 10\ kn\end{cases} \quad (4)$$

$$b_1 = \begin{cases}(1.6-0.14(10-u_0))L, \ u_0 \le 10\ kn \\ (1.6+0.14(u_0-10))L, \ u_0 > 10\ kn\end{cases} \quad (5)$$

Table 1 The pseudocode used for scenarios generation

	Algorithm Testing scenarios generation
1:	**Procedure:** Pseudocode for testing scenario generation
2:	**Input:** speed, weather, currents, vessels size, number of test points (n), number of ships, etc.
3:	**Generate** potential situations using SB, LH, RMC sampling
	For i=1:n % for all the sample points
4:	**Estimate** D_1 %distance between MASS and high speed craft $TCPA_1$ %time of closest approach $DCPA_1$ %distance of closest approach -- D_2 %distance between MASS and sailboat $TCPA_2$ %time of closest approach $DCPA_2$ %distance of closest approach -- a_1 %estimation of ellipse primary axis for OS b_1 %estimation of ellipse secondary axis for OS
5:	**If** D_1<D_2 **then**

6:	**If** $TCPA_1$>0 & $DCPA_1$<a_1 & D_1 <1nm **then**
	Situation should be considered
	Elseif $TCPA_2$ >0 & $DCPA_2$ < a_1 & D_2 < 1nm **then**
	Situation should be considered
	End if

7:	**Elseif** D_2<D_1 **then**

8:	**If** $TCPA_2$>0 & $DCPA_2$<a_1 & D_2 <1nm **then**
	Situation should be considered
	Elseif $TCPA_1$ >0 & $DCPA_1$ < a_1 & D_1 < 1nm **then**
	Situation should be considered
	End if

9:	**End if**
10:	**Calculate** the MSRE, mean for sampling methods
11:	**End** procedure

The performance of sampling techniques is assessed using the following criteria a) the number of identified collision scenarios; b) the difference between the anticipated and actual mean for one of the independent parameters that are not used as input to the metrics and criteria and c) the mean square root error (MSRE) of each sample for the independent parameter.

3 Investigated cases

For the analysis it is considered that we have a small ship (OS) having similar dimension with the one from the AUTOSHIP project [1] operating outside coasts of Norway. In the analysis OS is interacting with a sailing boat (TS1) and a high speed craft (TS2). The input parameters of the investigated situations are provided in Table 2. The random parameters with their ranges are provided in Table 3. These 18 parameters are varying from 0 to their maximum value by using the sampling technique which have been referred previously. For comparing sampling techniques from 100 up to 100,000 samples are considered. Wave height is used as an independent parameter to estimate the mean and MSRE. The test area is set to [0 3nm] x [0 3nm] in line with [5].

Table 2 The input parameters.

	Fish feeding vessel	**Sailboat**	**High speed craft**
Length	74.7m	6m	12m
Beam	13.6m	2m	2.5m
Max speed	15kn	10kn	40kn
Max current	3m/s		
Max waves height	2m		
Max wind speed	14 kn		

Table 3 The random parameters.

Random parameters	**Range**
Fish feeding vessel speed	[0 max]
Fish feeding vessel speed direction	[0 2pi]
Fish feeding vessel location	[0 3nm] x [0 3nm]
Sail boat speed	[0 max]
Sail boat speed direction	[0 2pi]
Sail boat location	[0 3nm] x [0 3nm]
High speed craft speed	[0 max]
High speed craft direction	[0 2pi]
High speed craft location	[0 3nm] x [0 3nm]
Current speed	[0 max]
Current direction	[0 2pi]
Waves height	[0 max]
Waves direction	[0 2pi]
Wind speed	[0 max]
Wind direction	[0 2pi]

4 Results and discussion

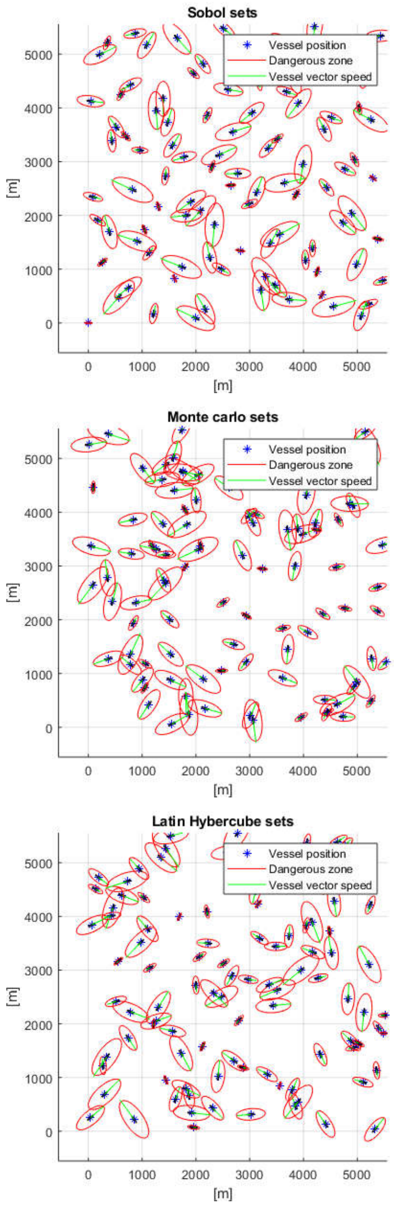

Figure 1: The filling of the test area using different sampling techniques

The coverage of the 3nmx3nm test area using the three sampling techniques in the present paper is provided in Figure 1 for 100 samples. It can be visually observed that the coverage of the area using SB sequences is more uniform that the other sampling techniques. For RMC sampling clustering of results can be observed e.g. at x=2000m and y=5000m. At the same coordinates at LH sampling a void can be observed.

Table 4 The comparison between different sampling techniques with 10^2, 10^3, 10^4, 10^5 samples

	N=	10^2	10^3	10^4	10^5
LH	Collision scenarios n	5.80	42.60	446	4548
	Waves height mean	1.01	0.99	0.98	0.99
	MSRE	0.35	0.33	0.33	0.34
RMC	Collision scenarios n	4.50	42.00	443.40	4564
	Waves height mean	0.98	0.98	0.99	1.00
	MSRE	0.32	0.36	0.34	0.33
SB	Collision scenarios n	4.00	40.00	476.00	4496
	Waves height mean	0.83	0.91	1.04	1.00
	MSRE	0.27	0.29	0.35	0.34

Further conclusions can be drawn from the MSRE and identified hazardous scenarios number correlated with the different sampling techniques in Table 4. The results are generated repeating the sampling 10 times for RMC and LH sampling technique and $N=10^2$, 5 times for RMC and LH and $N=10^3$ and 10^4 and 3 times for $N=10^5$ in Table 4. No repetition was required for SB samples, as it is a quasi-random technique.

It can be observed that SB samples in this algorithm identify similar number of hazardous scenarios that need to be considered for testing with other techniques with the effectiveness at 4.5% ($N=10^5$). Still, it can be also observed that out of the 100 potential encountering situations only 4 were classified as hazardous and relevant for testing on average for all the sampling techniques. It practically indicates that during automatic scenarios generation a lot of 'non-hazardous' encountering situations will be produced.

The stability of the results is the significant advantage of the SB sequences due to their quasi-random nature. As a consequence, there is no need to repeat the results saving computation time when applying SB sequences. Therefore, the SB sequence offers computational advantage at the same accuracy, compared with other sampling techniques and its use is favourable for the automatic test scenarios generation. This is in line with findings for SB from other engineering or mathematical problems [10-12].

The generated hazardous encountering conditions for total SB number N= 100 are provided in Figure 2. These are the scenarios that need to be considered for testing of the collision avoidance system on the OS. As it can be observed, the algorithm is effective in identifying hazardous situations that may occur between the OS and the other two TS. In this way, the sampling techniques can replace or support the Automatic Identification System (AIS) data used for traffic situations assessment. The generated data can be also used for finding clusters and the most hazardous situations in each cluster and further simplifications and enhancement of the testing procedures.

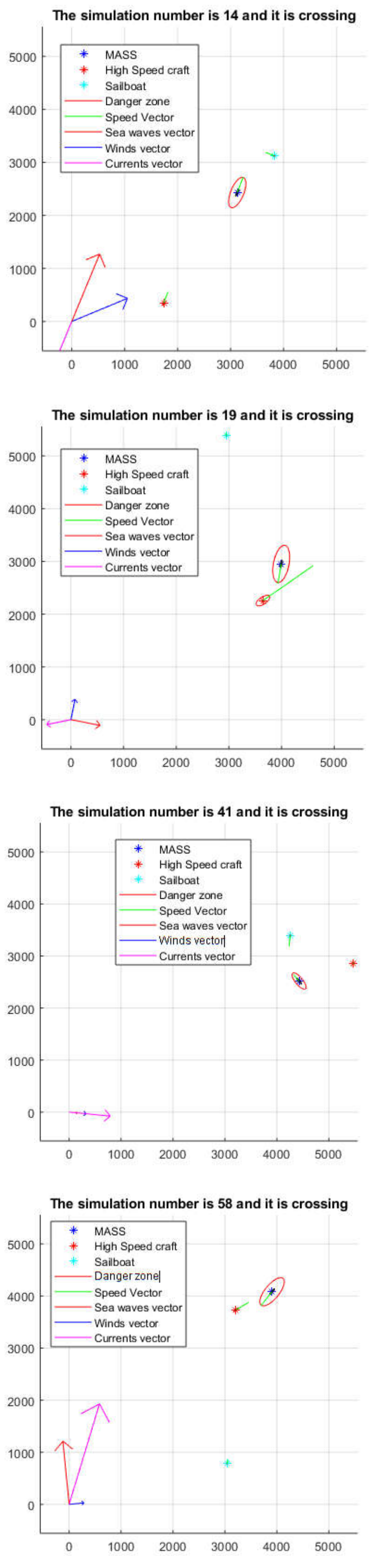

Figure 2: The hazardous encountering situations generated using Sobol sequences

5 Conclusions and further research

In this study an approach for automatic generation of hazardous conditions has been presented. It was found that:

- The approach can be used for generating hazardous conditions.
- The Sobol sampling provided accuracy comparable with other techniques with greater robustness.
- An alternative approach to generating traffic encounter conditions to that from AIS is proposed.

Our future work will focus on specifying more complex encountering conditions such as vessel in proximity to shore and analysis of the generated scenarios using clustering techniques.

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