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Semi-Markov Model of MASS Voyage

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ABSTRACT: The paper presents the readiness/safety model for the sea voyage of Maritime Autonomous Surface Ship (MASS), based on Semi-Markov process. The states of MASS during the voyage were defined as triplets of intentional type of MASS operations, reliability state and safety state, dependent on weather conditions. The determined states were aggregated, and the disjoint subsets were used to build a macro-model of MASS voyage process. An example of changes of MASS states during the sea voyage, for Gdynia - Port Everglades connection, is presented and discussed in the paper. The Semi-Markov process was used for the analysis of MASS reliability and safety during the sea voyage. The obtained matrix of transition probabilities between the states of MASS during the voyage can be used by MASS operator in Remote Operations Centre to make decisions related to voyage planning. The proposed model can constitute the basis of a computer program supporting the decision-making process of the operator.

1 INTRODUCTION

According to International Maritime Organization (IMO) Resolution A.893(21) "Guidelines for voyage planning", adopted on 25 November 1999, for crewed ships, the travel time, time of arrival at the destination port and the time in which the trip will be completed should be determined after completing the work related to the sea voyage planning. The same standards should be maintained in Maritime Autonomous Surface Ships (MASS) operation.

The implementation of MASS sea voyage plan is a subject to monitoring operational, technical and environmental parameters, control of a safety level and risk assessment by MASS operator in Remote Operation Centre (ROC). The responsibilities of the ROC operator are also making decisions related to necessary changes in the plan, changing the stages of the planned voyage or withdrawing from the plan.

Preparation for MASS sailing out to sea should meet the functional requirements to safely navigate in accordance with an appropriate voyage plan determining safe routes. The voyage plan should be approved by the responsible person to ensure safe navigation of MASS. A detailed voyage or passage plan should cover the entire voyage or passage from berth to berth. The voyage plan should be developed taking into account the following issues:

- the voyage plan should ensure that sufficient information is provided to operators to enable operations to be conducted with due regard to the safety of the ship and persons,
- navigational charts and publications should be updated with the latest available information [8, 9],
- a comprehensive information should be provided, including operational design domain (ODD) for autonomous navigation,
- it should be possible to define and update an itinerary, describing the complete voyage from

departure to arrival at the destination port, at any time,
- the crew and ROC operator should check the correct entry of the travel plan into ANS.

The model of MASS voyage safety proposed in the paper makes it possible to obtain information on the level of MASS safety at any stage of the sea voyage. The concept of a stochastic (random) process with a discrete set of states and a continuous set of parameters can be used to mathematically describe MASS during the sea voyage.

Constructing a model describing MASS during sea voyage should begin with defining the states. The state of MASS is determined by the state of its components at the moment t. The final form of the set of states of MASS during a sea voyage depends on the modeling purpose. The model should facilitate the ROC operator in making decisions leading to the safe completion of the MASS sea voyage. The weather [2, 3], port infrastructure [4] conditions and psychophysical condition of the ROC operator [1] plays an important role in this process. In the presented model only the weather conditions are considered.

The most important issue in constructing a random process, is to define the possible states of the MASS unit during the sea voyage.

2 STATES, PARAMETERS AND CHARACTERISTICS OF MASS

The states of MASS during the voyage should be defined including:
- information on the intentional type of operation at a given moment,
- information on the technical condition of MASS, i.e. reliability and safety status depending on hydrometeorological conditions.

Each state of MASS can be described as a triplet (1):

$$S_{ijk} = (i, j, k) \tag{1}$$

where:
i - intentional operational state of MASS,
j - reliability state of MASS,
k - safety state of MASS.

The possible operating, reliability and safety states of MASS are presented in Tables 1 - 3.

Table 1. Operating states of MASS

i	Intentional operational state of MASS
1	Completion of loading operations, preparation for departure
2	Port maneuvers, leaving the port
3	Sea voyage
4	Approach maneuvers, entering the port, port maneuvers, berthing and mooring

Table 2. Reliability states of MASS

j	Reliability state of MASS
0	Unsuitability
1	Partial suitability
2	Suitability

Table 3. The possible safety states of MASS

k	Intentional safety state of MASS
0	Inability to complete the voyage
1	Relative hazard to safety
2	Complete safety

The states defined above combined in triplets describe MASS state, for example the state Sijk=(3,2,1) means that MASS is on a sea voyage, in full suitability state (in fully technically fit) and is in a state of relative safety hazard, while the state Sijk =(3,1,2) means that the MASS is on a sea voyage, in partial suitability state (in partially technically fit) and in state of complete safety.

The set of all possible states S in this case consists of: 4 x 3 x 3 = 36 elements.

Such a number of states for a single unit is too large to build a macro-model of the sea voyage process. Therefore, states are aggregated, creating disjoint subsets (2):

$$\begin{aligned}
Z_0 &= \{(1,0,0),(1,0,1),(1,0,2),(1,1,0),(1,2,0)\ldots \\
&\quad (4,0,0),\ (4,0,1),\ (4,0,2),\ (4,1,0),\ (4,2,0)\}, \\
Z_1 &= \{(1,1,1),\ (1,1,2),(1,2,1)\}, \\
Z_2 &= \{(2,1,1),\ (2,1,2),(2,2,1)\}, \\
Z_3 &= \{(3,1,1),\ (3,1,2),(3,2,1)\}, \\
Z_4 &= \{(4,1,1),\ (4,1,2),(4,2,1)\}, \\
Z_5 &= \{(1,2,2)\}, \\
Z_6 &= \{(2,2,2)\}, \\
Z_7 &= \{(3,2,2)\}, \\
Z_8 &= \{(4,2,2)\}.
\end{aligned} \tag{2}$$

3 MODEL OF THE SEA VOYAGE PROCESS OF THE MASS UNIT

The subsets Z0, Z1, ..., Z8 are taken as the final states of MASS during her sea voyage. To facilitate the description, we can replace symbols denoting states with their numbers Z_k\leftrightarrow k,\vthicksp k=0,1,2,...,8.

The process states are defined in Table 4.

Table 4. States of MASS sea voyage process

k	State of MASS
0	Total unsuitability to perform sea voyage
1	Completion of loading operations, preparation for departure of MASS in partial suitability state and/or with relative hazard to safety
2	Port maneuvers, leaving the port of MASS in partial suitability state and/or with relative hazard to safety

3 Sea voyage of MASS in partial suitability state and/or relative hazard to safety
4 Port maneuvers, entry to the port, berthing and mooring of MASS in partial suitability state and/or with relative hazard to safety
5 Completion of loading operations, preparation for departure of MASS with total technical suitability and/or complete safety state
6 Port maneuvers, leaving the port of MASS with total technical suitability and/or complete safety state
7 Sea voyage of MASS with total technical suitability and/or complete safety state
8 Port maneuvers, entry to the port, berthing and mooring of MASS with total technical suitability and/or complete safety state

An example of changes of MASS states during the sea voyage is presented for Gdynia - Port Everglades connection for the assumed four variants of this sea route.

The variants of Gdynia - Port Everglades route are presented in Figure 1.

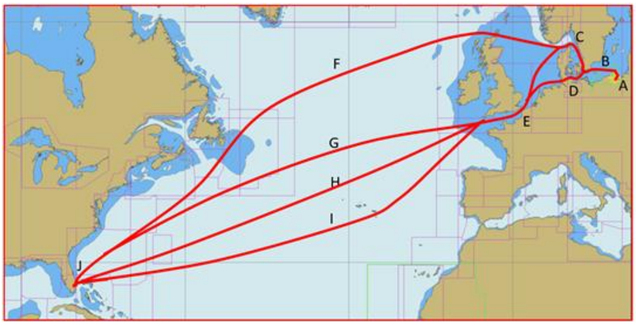

Figure 1. Gdynia - Port Everglades variants of MASS sea routes

The MASS states changes can be presented in a graph, showing all possible assumed states and transitions between the states.

The graph of changes in MASS states during Gdynia - Port Everglades sea voyage, computed for the assumed sea routes is presented in Figure 2.

The symbols used in the graph, including four MASS route variants are as follows:

– A – Gdynia
– B – Hammerodde Fyr (Bornholm)
– C – Skagen
– D – Kiel Canal
– E – English Channel, Dover Strait
– F – Port Everglades - Pentland Firth
– G – Port Everglades – Falmouth (Great Circle)
– H – Port Everglades – Falmouth (rhumb line)
– I – Port Everglades – Falmouth via Acores

Constructing the MASS sea voyage process, the probabilistic characteristics, generating the process implementation are assigned to the directed arcs of the graph.

If the process describing MASS during a sea voyage takes values in the subset of states S_2={5,6,7,8}, this means that the MASS sea voyage goes normally. If this process takes values in the set S_1={1,2,3,4}, this means that the MASS sea voyage is subject to disruptions caused by her technical condition and/or hydrometeorological conditions resulting, i.a in increased hazard to safety during the sea voyage. The process state defined by the single-element subset S_0={0}, means that MASS is not conducting a sea voyage and may be in a state of failure and/or with relative hazard to safety.

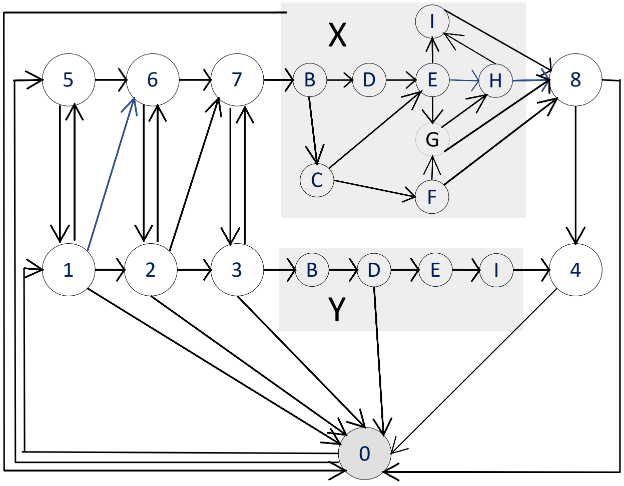

Figure 2. Graph of changes in MASS unit states during Gdynia - Port Everglades sea voyage, developed for the assumed four (F – I) Gdynia - Port Everglades sea routes

To construct the MASS sea voyage process, the directed arcs of the graph (Fig. 2) should be assigned probabilistic characteristics that generate realizations of the process. The arc (*i*, *j*) corresponds to the probability of changing state from *i* to *j*, which is denoted by the symbol p_{ij} and the distribution function $F_{ij}(t)$ of the random variable T_{ij} denoting the duration of state *i* when the next state will be state *j*.

Then the function Q_{ij}(t) (3) is the probability of changing state from i to j in time no longer than t.

$$Q_{ij}(t) = p_{ij} F_{ij}(t), \quad t \geq 0 \tag{3}$$

Determining the transition probabilities functions for individual arcs of the graph from equation (3), we can determine a functional matrix *Q(t)*, called the kernel [5, 6, 7], which, together with the initial distribution, defines the Semi-Markov process {*X(t)*: *t* ≥ 0} with the set of states *S*={0,1,2,…,8}.

The kernel of the Semi-Markov process has the following form (5):

$$Q(t) = \begin{bmatrix} 0 & Q_{01}(t) & 0 & 0 & 0 & Q_{05}(t) & 0 & 0 & 0 \\ Q_{10}(t) & 0 & Q_{12}(t) & 0 & 0 & Q_{15}(t) & Q_{16}(t) & 0 & 0 \\ Q_{20}(t) & 0 & 0 & Q_{23}(t) & 0 & 0 & Q_{26}(t) & Q_{27}(t) & 0 \\ Q_{30}(t) & 0 & 0 & 0 & Q_{34}(t) & 0 & 0 & Q_{37}(t) & 0 \\ Q_{40}(t) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & Q_{51}(t) & 0 & 0 & 0 & 0 & Q_{56}(t) & 0 & 0 \\ 0 & 0 & Q_{62}(t) & 0 & 0 & 0 & 0 & Q_{67}(t) & 0 \\ 0 & 0 & 0 & Q_{73}(t) & 0 & 0 & 0 & 0 & Q_{78}(t) \\ Q_{80}(t) & 0 & 0 & 0 & Q_{84}(t) & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

The sea voyage process of MASS defined in this way allows the use of Semi-Markov process to analysis of the reliability and safety of the unit.

The theory of Semi-Markov processes [5, 6, 7] results in the following property:

$$p_{ij} = \lim_{t \to \infty} Q_{ij}(t), \quad t \geq 0 \tag{5}$$

In the presented model, using equations (3), (4) and property (5), we can obtain a matrix of transition probabilities between states for the considered MASS during her sea voyage (6).

$$P=\begin{bmatrix} 0 & p_{01} & 0 & 0 & 0 & p_{05} & 0 & 0 & 0 \\ p_{10} & 0 & p_{12} & 0 & 0 & p_{15} & p_{16} & 0 & 0 \\ p_{20} & 0 & 0 & p_{23} & 0 & 0 & p_{26} & p_{27} & 0 \\ p_{30} & 0 & 0 & 0 & p_{34} & 0 & 0 & p_{37} & 0 \\ p_{40} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p_{51} & 0 & 0 & 0 & 0 & p_{56} & 0 & 0 \\ 0 & 0 & p_{62} & 0 & 0 & 0 & 0 & p_{67} & 0 \\ 0 & 0 & 0 & p_{73} & 0 & 0 & 0 & 0 & p_{78} \\ p_{80} & 0 & 0 & 0 & p_{84} & 0 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

The determined probabilities can be used by the ROC operator to make decisions related to the planning and implementation of MASS sea voyage.

The readiness/safety model for the sea voyage of MASS is presented in Figure 3.

In order for the ROC operator to make decisions, the critical values of probabilities were determined in the following ranges $R_{MASS}<0.5$, $0.5\le R_{MASS}\le 0.8$ and $R_{MASS}>0.8$.

Depending on the situation from which range we received the values of the probability of transition between states generated in the matrix, we have a different decision scenario.

If $R_{MASS}>0.8$, it means that the task can be carried out without disruptions and that the unit is in the highest reliability state and there are no threats to its safety. Then the operator can, for example, choose any variant of route form X variants (Figure 2).

If $0.5\le R_{MASS}\le 0.8$, it means that the unit is in a state of intermediate airworthiness and in an intermediate state of safety, which means that the operator must identify the reasons of this state and decide to continue the task and choose the route from variants Y, e.g. the more safe route variant, or one of the states: reliability or safety should be improved by for example repairing or changing the course in order to improve the ship's performance in difficult weather conditions.

When $R_{MASS}<0.5$, it means that there is little chance of completing the task or continuing the journey, MASS is at risk and a decision should be made either to interrupt the journey or to increase the probability by increasing the reliability and safety status to allow the MASS voyage to continue.

4 DISCUSSION AND CONCLUSIONS

The model of safety and reliability of an autonomous unit proposed in the paper, during the implementation of a transport task, using semi-Markov processes, can support ROC operator decision-making related to voyage planning and conducting.

It can also contribute to ensuring an appropriate level of safety.

The final effect of the model is a matrix of transition probabilities between states. In reliability models, the characteristics of Semi-Markov process translate into the reliability characteristics of the modeled object MASS.

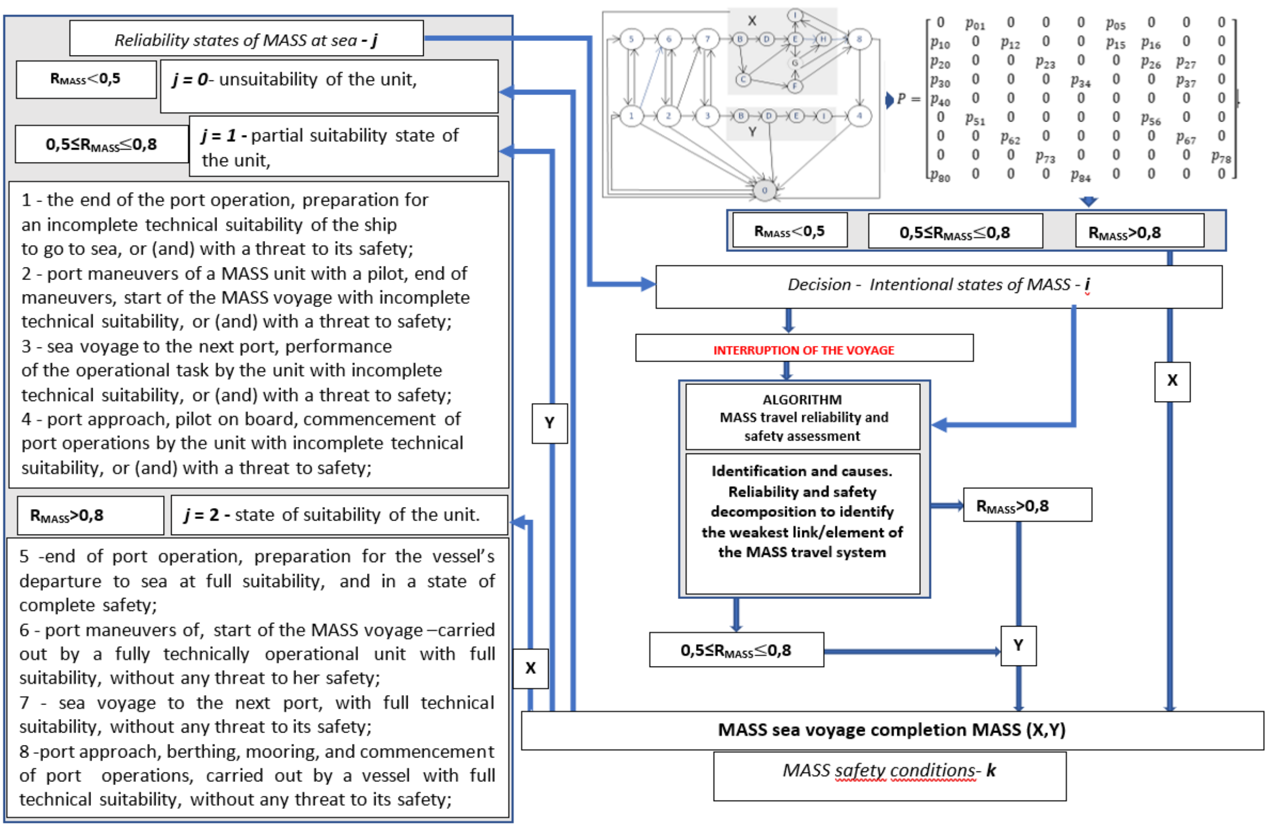

Figure 3. Readiness/safety model of MASS sea voyage

The determined probabilities give us information about the probability with which MASS is able to perform a given task under current weather conditions and in its current technical condition. In other words, we can say how reliable it is to perform a given task.

The proposed model can constitute the basis of a computer program supporting the decision-making process of the operator of an autonomous unit.

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