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PROPOSAL OF MULTI CRITERIA DECISION PROCESS OF VESSEL ROUTE SELECTION FOR A VTS SYSTEM

The paper introduces a multi criteria vessel route selection process designed for the VTS system. The process utilizes simulation routines and a multi criteria decision method to create a ranking of all considered routes. The proposed solution is illustrated by the vessel route selection example taking advantage of the method chosen.

PROPOZYCJA PROCESU WIELOKRYTERIALNEGO WYBORU MARSZRUTY STATKU DLA POTRZEB SYSTEMU VTS

W artykule proponowany jest proces wielokryterialnego doboru trasy statku przez system VTS. Proces ten wykorzystuje mechanizmy symulacji oraz metody rozwiązywania wielokryterialnych problemów decyzyjnych w celu stworzenia rankingu preferowanych tras. Proponowane rozwiązanie zilustrowane jest przykładem doboru trasy statku dla tej metody.

1. INTRODUCTION

Route selection is a vital decision problem faced by the navigators of the sea going vessels. The navigators ought to choose the best possible route whenever there is an alternative. This selection is often made based on the length of the routes, their hydro-navigational conditions, etc. It is substantial to make the selection dependent also on the predicted collision risk, the major factor describing vessel's security. This is commonly estimated by the expected number of encounters for a route [3]. This paper proposes another approach towards risk collision estimation and incorporates this proposal into the general process of route selection system designed for the Vessel Traffic Service (VTS) system.

The following sections are organized as follows: section 2 briefly describes the controlling role of the VTS system and provides a description of the vessel route selection process for the VTS system including all the key elements of the proposal. Section 3 provides a numerical example of a route selection problem exemplifying the previously described process. Finally, section 4 presents the conclusions.

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2. DESCRIPTION OF A VESSEL ROUTE SELECTION PROCESS FOR THE VTS SYSTEM

The main purpose of a Vessel Traffic Service (VTS) is to control navigable waterways and provide navigational aid for vessels in order to prevent them from collisions and groundings. Such services prove to be particularly valuable in confined waterways, e.g. harbour approaches. VTS systems may oblige vessels passing the controlled waterways to send their identity and location information such as current velocity and course. In return VTS broadcasts reports on the positions of other traffic in the area, waterway and weather conditions or navigational hazards, but also is able to restrict vessels to use only advised routes.

The idea of a vessel route selection process for the VTS system is based on the assumption that the VTS system is aware of current locations, velocities and courses of all the vessels in the controlled area. Before passing the area controlled by the VTS and having a specific number of alternative routes, navigator of a ship requests the VTS operator for a recommendation which route to choose. The VTS operator then initialises the vessel route selection process setting the ship as the own ship and all the other vessels in the area as target ships. When the process finalizes VTS operator sends to the navigator the recommendation obtained as a final result of the in-process computations.

The route selection process consists of three cooperating modules: simulation, risk estimation and multi criteria decision module. Next sections provide detailed description of the modules.

2.1. SIMULATION MODULE

The main goal of the simulation module is to predict the trajectories of the own ship as well as all the target ships that might collide with her. One simulation run makes a prediction for one of the alternative routes. The following assumptions have been made here:
- all ships go with linear course and constant velocity,
- all ships have circular domains of configurable size assigned,
- an anti-collision manoeuvre is possible only due to course alteration, no velocity alteration is taken into account,
- in accordance with the COLREG rules all the encounters are divided into three distinctive classes: crossing, head-on and overtaking encounters and the distinction between these classes is based on the courses of the ships taking part in the encounter,
- when an encounter occurs, a decision is made, based on the COLREG rules, which ship is to give way and thus to perform an anti-collision manoeuvre:
  - for crossing encounters the ship that has the other ship on her starboard is required to give way,
  - for head-on encounters both ships are required to perform anti-collision manoeuvres,
  - for overtaking encounters the ship that overtakes the other ship must avoid crossing with the overtaken one.

Based on the assumptions listed above, a computer simulator has been implemented. It requires the following input data:

- initial and goal positions of the own ship and all the target ships,
- the velocities of the own ship and all the target ships,
- the domain radius of the own ship and all the target ships,
- the radius of the radar visibility area (arena [2]) for the own ship.

Once all the input parameters are collected the simulation process can be initiated. After triggering the simulator computes all the current positions of the vessels for given moment of time. Within each next step the current time is increased by one unit and all the current positions of the vessels are recalculated. In order to avoid collisions between the own ship and the target ships, the area of own ship arena is checked for occurrence of target ship in each simulator step. Whenever a target ship gets into the own ship's arena, it is first inspected whether keeping current courses of both ships would result in a close quarter encounter. The notion of DCPA (distance at the closest point of approach) [4] is utilized to check for possible own ship domain being violated. This is done according to the formulas:

$$TCPA_j = -\frac{XV_{wx} + YV_{wy}}{V_w^2},$$

(1)

$$DCPA_j = \left| \begin{cases} Ds & when\, TCPA_j < 0, \\ \left| \dfrac{XV_{wy} - YV_{wx}}{V_w} \right| & when\, TCPA_j \geq 0, \end{cases} \right.$$

(2)

where:

$TCPA_j$ - time remaining to reach the distance at the closest point of approach between the own ship and the j-th target ship,

$DCPA_j$ - distance at the closest point of approach between the own ship and the j-th target ship,

D_S - safe distance of approach (radius of the circular ship domain) of the own ship,

X, Y - relative distances between the own and target ship for OX and OY axes respectively,

V_w - module of the relative velocity for the own and target ship, $V_w^2 = V_{xw}^2 + V_{wy}^2$.

When the $DCPA_j$ distance is equal to or lesser than the radius of the own ship domain, then it is expected that the own ship domain would be violated and an anti-collision manoeuvre is required. Next to that, based on the COLREG rules, a decision is made which of the ships is to give way. The required minimal course alteration is then calculated according to the formula [7]:

$$\Delta \Psi_{L/R} = \pm \delta_j + q_j - \arcsin\left(\frac{V_j}{V}\sin\left(\pm \delta_j + N_j - \Psi_j\right)\right), \quad \delta_j = \arcsin\left(\frac{D_S}{D_{AB_j}}\right), \quad q_j = N_j - \Psi,$$

(3)

where:

$\Delta \Psi_{LR}$ - required minimal course alteration on either starboard or portboard,

D_S - safe distance of approach of the own ship,

D_{ABj} - actual distance between the own ship and the j-th target ship,

δ_j *- collision risk angle for the own ship and the j-th target ship,*
Ψ, Ψ_j *- courses of the own ship and the j-th target ship respectively,*
N_j *- bearing on the j-th target ship,*
V, V_j *- velocities of the own ship and the j-th target ship respectively.*

The give-way ship changes her course accordingly and keeps the altered course until the distance d_{alter} is covered:

$$d_{alter} = TCPA * V + D_S$$

(4)

where:

TCPA   *- time remaining to reach the distance at the closest point of approach between the give-way ship and the stand-on ship,*

V   *- velocity of the give-way ship,*

D_S *- safe distance of approach (radius of the circular ship domain) of the give-way ship.*

Once the d_{alter} distance is covered, the give-way ship changes her course again to get back to the former course and after covering another d_{alter} distance it is back to her original course. Then the simulation process continues until the own ship reaches her goal position or its near proximity.

2.2. RISK ESTIMATION MODULE

Calculations of possible collision risk are made and stored for future utilization by the risk estimation module during each simulation run. Whenever an expected encounter between the own and target ship is registered and appropriate anti-collision actions are about to be taken, the process calculates risk of collision utilizing the following formula [5]:

$$r_j = \frac{1}{\sqrt{a_1 \left(\frac{DCPA_j}{D_S} \right)^2 + a_2 \left(\frac{TCPA_j}{T_S} \right)^2 + a_3 \left(\frac{D_j}{D_S} \right)^2}}$$

(5)

where:

r_j *- collision risk between the own ship and the j-th target ship,*

$DCPA_j$ *- distance at the closest point of approach between the own ship and the j-th target ship,*

$TCPA_j$ *- time remaining to reach the distance at the closest point of approach between the own ship and the j-th target ship,*

D_j *- actual distance between the own ship and j-th target ship,*

D_S *- safe distance of approach (radius of the circular own ship domain),*

T_S *- safe time, which is necessary to plan and execute a collision avoidance manoeuvre,*

a1, a2, a3   *- weight coefficients dependent on the weather and hydro-navigational conditions.*

Since certainty of each encounter diminishes with the number of prior encounters it is justified to model the probability of no collision by a fuzzy number [1, 6] instead of a crisp value. Thus, when a collision risk r_j (a crisp value) is calculated, the crisp probability $P_{NO\ COLL\ j}$ of no collision between the own and j-th target ship is determined as:

$$P_{NO\ COLL\ j} = 1 - r_j$$

(6)

and then the crisp value of $P_{NO\ COLL\ j}$ is converted into a triangular fuzzy value [1] $P_{F\ NO\ COLL\ j}$:

$$P_{F\ NO\ COLL\ j} = (P_{NO\ COLL\ j} - e * \gamma ; P_{NO\ COLL\ j} ; P_{NO\ COLL\ j} + e * \gamma)$$

(7)

where:

$P_{F\ NO\ COLL\ j}$ - *probability of no collision between the own ship and the j-th encountered ship represented by a triangular fuzzy value (a;b;c),*

e - *number of prior encounters in the simulation,*

γ - *constant value of risk discount rate, e.g. $\gamma = 0.001$.*

The risk estimation module collects the $P_{F\ NO\ COLL\ j}$ values separately for every target ship and encounter class (crossing, head-on and overtaking) during the simulation run. Finally, when the simulation is finished, the total probability of no collision for each encounter class is computed as a multiplication of $P_{F\ NO\ COLL\ j}$ probabilities for all the target ships (j=1..k):

$$P_{TOTAL\ NO\ COLL\ ENC\_CLASS} = P_{F\ NO\ COLL\ 1\ ENC\_CLASS} * P_{F\ NO\ COLL\ 2\ ENC\_CLASS} * ... * P_{F\ NO\ COLL\ k\ ENC\_CLASS}$$

(8)

The multiplication of two triangular fuzzy values e.g.: $v_1 = (a_1;b_1;c_1)$ and $v_2 = (a_2;b_2;c_2)$ does not necessarily yield another triangular fuzzy value, as proven in [1]. However, in case of triangular fuzzy values with symmetrical membership function, such as $P_{F\ NO\ COLL\ j\ ENC\ CLASS}$ values, the membership function of the resulting fuzzy value might be approximated simply by a triangular function:

$$v_1 * v_2 \cong (a_1 * a_2 ; b_1 * b_2 ; c_1 * c_2)$$

(9)

which simplifies the calculations of $P_{TOTAL\ NO\ COLL\ ENC\ CLASS}$ and makes it a triangle fuzzy value.

2.3. MULTI CRITERIA DECISION MODULE

When all the simulations are completed (one simulation run for each alternative route) and the outcome of the risk estimation module is available, multi criteria decision module is able to create a ranking of the routes. The goal is to select the best of the available routes taking into consideration decision criteria describing the known as well as the estimated route's data. One of the most useful multi criteria decision method for this module is Fuzzy TOPSIS method [1], described earlier in navigational context in [6]. The Fuzzy TOPSIS

method extends the original TOPSIS method by additional support of criteria and their weights described by the triangular fuzzy values or linguistic variables. A software tool for Fuzzy TOPSIS computations has already been implemented.

In order to perform Fuzzy TOPSIS computations some preliminary configuration is required first. Each route constitutes separate alternative. The criteria are selected among the deterministic data (such as route's length) and estimated data (such as $P_{TOTAL\ NO\ COLL\ ENC\ CLASS}$). In addition, the Fuzzy TOPSIS weight vector W, described in [1, 6], must reflect user preferences for the given criteria set. Table 1 presents an example criteria set and weight vector values designed for the vessels route selection decision module.

Table 1

Example of a criteria set and weight vector values for the decision module of the vessel route selection process

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
Criterion name	Route length [Nm]	Hydro-navigational conditions [/]	$P_{TOTAL\ NO\ CROSSING}$ [/]	$P_{TOTAL\ NO\ HEAD-ON}$ [/]	$P_{TOTAL\ NO\ OVERTAKING}$ [/]
Criterion description	cost criteria described by a crisp value	quality criteria described by a linguistic variable (represented by triangular fuzzy values)	quality criteria described by a triangular fuzzy value	quality criteria described by a triangular fuzzy value	quality criteria described by a triangular fuzzy value
Weight vector value W_i	0.1	0.1	0.4	0.2	0.2

Once the data set (decision matrix D described in [1, 6]) is properly configured, Fuzzy TOPSIS method produces a ranking of alternatives (here – routes). The best alternative with the highest ranking index will be the route recommended by the VTS operator to the navigator of the own ship as the safest and the most convenient.

3. EXAMPLE OF THE ROUTE SELECTION PROCESS FOR THE VTS SYSTEM

Now let's consider the following scenario. A ship's navigator has three alternative routes possible for harbour approaching and thus he requests a VTS operator for a recommendation of a best one. The VTS system is able to obtain full information about current vessel's positions for the routes considered as illustrated in fig.1 – 3. The VTS operator having known all the initial locations, velocities and courses of the other vessels (target ships) in the area initiates the vessel (own ship) route selection process by starting the simulation routine separately for each of the routes.
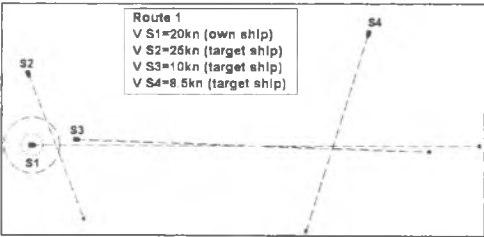

Route 1
V S1=20kn (own ship)
V S2=25kn (target ship)
V S3=10kn (target ship)
V S4=8.5kn (target ship)

Route 2
V S1=20kn (own ship)
V S2=25kn (target ship)
V S3=20kn (target ship)
V S4=8kn (target ship)

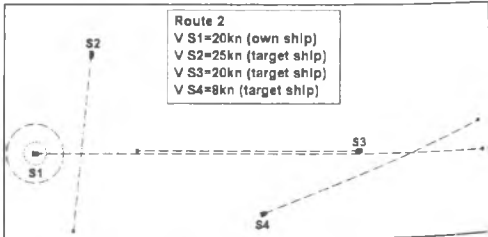Fig.1. Initial vessels' positions and courses - route 1   Fig.2. Initial vessels' positions and courses - route 2
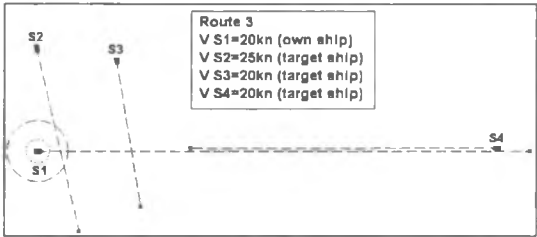
Fig.3. Initial vessels' positions and courses - route 3

Table 2 depicts the outcome of the simulation and risk modules. The number of expected encounters for the routes is divided out between the encounter classes. Also the total probabilities of no encounter of given class for a route are given.

Table 2

Expected own ship encounters and probabilities of no encounter of a given class for routes 1-3

	Number of crossing encounters	P TOTAL NO CROSSING	Number of head-on encounters	P TOTAL NO HEAD-ON	Number of overtaking encounters	P TOTAL NO OVERTAKING
Route 1	1	(0.633; 0.640; 0.646)	0	(1; 1; 1)	1	(0.735; 0.735; 0.735)
Route 2	0	(1; 1; 1)	1	(0.562;0.562;0.562)	1	(0.688; 0.695; 0.702)
Route 3	1	(0.618; 0.618; 0.618)	1	(0.556;0.562;0.568)	0	(1; 1; 1)

Once the simulation sub-process is finished and information about the length of the routes as well as their hydro-navigational conditions is collected, the decision matrix D (Table 3) is constructed and becomes an input data of the multi criteria decision module for given set of routes.

Table 3

Decision matrix (D) for the routes 1-3 as an input data of the multi criteria decision module

	Route length [Nm]	Hydro-navigational conditions [/]	P TOTAL NO CROSSING [/]	P TOTAL NO HEAD-ON [/]	P TOTAL NO OVERTAKING [/]
Route 1	40.1	good (0.6; 0.8; 1)	(0.633; 0.640; 0.646)	(1; 1; 1)	(0.735; 0.735; 0.735)
Route 2	41.9	poor (0; 0.2; 0.4)	(1; 1; 1)	(0.562;0.562;0.562)	(0.688; 0.695; 0.702)
Route 3	42.3	good (0.6; 0.8; 1)	(0.618; 0.618; 0.618)	(0.556;0.562;0.568)	(1; 1; 1)

Table 4

Ranking of routes 1-3 as an outcome of the multi criteria decision module

	Route 1	Route 2	Route 3
Ranking index [/]	0.411	0.555	0.327

For the preliminary configuration of the multi criteria decision module adopted from section 2.3, Fuzzy TOPSIS method produces its final ranking as given in Table 4. The Fuzzy TOPSIS ranking shows that the best alternative route among the routes 1-3 is route 2, and the route 1 is the runner-up. Route 3 closes the ranking with the smallest index value. The fact that the route 2 has obtained the highest ranking index is caused mostly by the highest

probability of no crossing encounters (the most important criterion, W_i=0.4) for the route and significant probability of no head-on encounters (even though the hydro-navigational conditions are far from ideal - the least important criterion, W_i=0.1).

Having analysed the outcome of the multi criteria decision module, the VTS operator would recommend the route 2. It is worth noticing though, that all the three considered routes have total number of encounters equal to 2. Thus, estimating the collision risk only by the number of encounters would not be sufficient to differentiate between these routes.

4. CONCLUSIONS

In the paper a proposal of a vessel route selection process for the VTS system has been presented. A detailed description of the modules comprising the process is provided. This is illustrated by a numerical example of possible application of the proposal. The process proves to be useful when a recommendation for a route is requested, especially when the expected number of encounters is not a sufficient risk estimator. Current solution, including the software tools, might be easily integrated with the VTS system providing additional support for the VTS operator.

In the nearest future continuation of the research is planned. Possible extensions include velocity alteration for anti-collision manoeuvres and introducing different domain shapes.

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