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The safe ships trajectory in a restricted area

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Abstract
This paper presents the problem of determining a safe ship trajectory in a restricted area. The route choice task is defined as a dynamic optimization problem. The route choice algorithm and criteria are presented and discussed. The ship fuzzy domains are used as a safety criterion. The criterion of the number of manoeuvres to be performed by the own ship is added to the algorithm. The ship encounters simulated situations. Calculated safe ship trajectories were presented and discussed. Discusses the implementation of the present process, in real terms.

Introduction

Ensure the safety of passengers, cargo, and the environment is one of the basic tasks navigator. This involves the need to determine a safe ship trajectory and its modifications if the situation is changing. The most important criteria for trajectory choice are safety and cost-effectiveness. The basic constraints for the trajectory choice in an open sea area are ship encounters, hydrological and meteorological conditions and own ship manoeuvring ability.

Navigation in restricted areas should take into account water area parameters – length, width and depth.

As in restricted waters traffic is often dense, the issue of safe trajectory of the vessel is essential.

It seems that soon the automatic determination of a safe ship trajectory will become an available basic functionality in ship navigational decision support systems. It is important to apply criteria similar to the criteria used by navigators at the sea. This will allow to generate solutions in accordance with navigators expectations and use the generated solutions (trajectories) in conducting the ship.

One of the possibilities is the use of the fuzzy sets theory methods and tools for the formulation of safe ship trajectory determination criteria. This paper continues the authors' previous work in this field [1].

Ship trajectory choice in restricted waters

Restricted water areas are characterized by the lack of free route choice and the need to use safety principles taking into account local conditions and regulations. The choice of a specific trajectory requires mostly a greater number of constraints, in particular the shoreline, shallows and other navigational dangers. The choice criteria, in particular safety criteria (passing another ship, navigational hazards or offshore / port structures) should be in general modified.

Planning a ship's trajectory refers to solving situations of encountering other vessels (targets) and stationary objects in order to pass them safely. The navigator, planning a manoeuvre, bears in mind the constraints (navigable area limits, ship's manoeuvrability) and uses certain criteria [1, 2]:

- safety criteria:
  - safe distance of passing, overtaking or crossing target's course;
  - safe distance of passing stationary objects: land, navigational dangers;
- criteria derived from regulations in force and good sea practice [3]:

  - course alteration, readily apparent to another vessel;
  - sufficiently early performance of the manoeuvre;
  - manoeuvre recommended by regulations;
- economic criteria: loss of time, distance covered, fuel consumption etc.

The basic criteria are safety criteria. The closest point of approach (CPA) is the common criterion used in open sea areas. However, the use of the mentioned criterion on the restricted area is often impossible. The reason may be the width of the waterway.

The criterion of ship domain is an alternative to CPA. The authors propose two- and three-dimensional domains. The two-dimensional domain is an area around the ship that its navigator should keep clear of other vessels and objects [4, 5].

The ship fuzzy domain is an extended domain concept [6]. This is an area around the ship that the navigator should keep clear of other vessels and objects, and the shape and size of this area depend on the assumed level of navigational safety, understood as a degree of membership of a navigational situation to the fuzzy set "dangerous navigation".

The shape and size of ship domain and ship fuzzy domain depend on many factors, which makes its determination difficult. This problem is discussed in a number of publications, for example [4, 5, 6, 7, 8, 9].

In most cases a domain is assigned to the object for which a safe trajectory is being determined – own ship. In an alternative approach domains can be assigned to targets [8, 10]. In this case our (own) ship is considered as a point. This also requires that domains be assigned to other objects – navigational dangers.

An important supplement to the mentioned safety criteria are criteria resulting from the regulations in force and principles of good sea practice: substantial and visible course alteration, sufficiently early performed manoeuvre, recommended turn to starboard. The substantial course alteration is understood as such alteration that will be noticed by the navigators on ships in vicinity. When a dangerous situation occurs (risk of collision), the navigator should take preventive actions early enough to solve the collision situation. The regulations recommend turn-to-starboard manoeuvre to solve a collision situation.

Economic criteria are also very important, being mainly requirements imposed by the shipowner. These are mostly formulated as loss of time, extra distance covered, fuel consumption etc. Acceptable values of these losses in some cases may be determined.

Ship trajectory determination as an optimization task

The route choice is associated with the determination of manoeuvre / manoeuvres and its / their parameters to ensure the safe passing of encountered objects [9]. This task can be formulated as the ship's course and/or speed determination.

The movement control of a ship which represents a multidimensional nonlinear dynamic object, requires multiple decision making. Decisions are dynamic and involve the settings of controls (rudder, machine) in order to execute an effective manoeuvre.

The problem of ship trajectory determination can be formulated as a dynamic optimization task. The problem leads to the formulation of multicriteria optimization when additional criteria, such as e.g. loss of way, fuel consumption are taken into account.

One of the standard methods of dynamic optimization is dynamic programming, used in problems of multistage decision making and control. Optimal ship control in terms of preset control quality indicator can be determined by using the Bellman's principle of optimality.

The optimization problem is to find such control function $\mathbf{u}(t)$, defining the optimal trajectory $\mathbf{x}(t)$ that the quality functional J will assume a minimum value:

$$J(\hat{\mathbf{x}}(t), \hat{\mathbf{u}}(t), t) = \\ = \min_{\mathbf{u}(t)\in\mathbf{U}_0,\, \mathbf{x}(t)\in\mathbf{X}_0} \int_{t_0}^{t_k} f_0(\mathbf{x}(t), \mathbf{u}(t), t)\,\mathrm{d}t \tag{1}$$

where:

$\mathbf{X}\{x_1, \ldots x_n\}$ – n-dimensional space of states $\mathbf{X}$;
$\mathbf{U} = \{u_1, \ldots u_m\}$ – m-dimensional space of controls $\mathbf{U}$;
f_0 – function of instantaneous losses;
$\mathbf{u}(t)\in\mathbf{U}_0$ – set of allowable controls;
$\mathbf{x}(t)\in\mathbf{X}_0$ – allowable (maximal) trajectory space;
t – time;
t_0, t_k – start and stop time.

The control strategy, determining the optimal trajectory, consists of a series of controls:

$$\hat{u} = \left(\hat{u}_{t_o}, \hat{u}_{t_1}, \ldots, \hat{u}_{t_{k-1}}\right) \tag{2}$$

where:

$\hat{u}_{t_i}$ – control in time t_i, $i = 0,1, \ldots, k$.

Uncertainties (imprecisions) of goals and constraints in the trajectory choice can be accounted for by using systems of fuzzy inference, including systems employing methods of multistage control in a fuzzy environment [11, 12].

Multistage control in a fuzzy environment

The fuzzy environment can be presented as an ordered four $\langle \boldsymbol{G}, \boldsymbol{C}, \boldsymbol{D}, \boldsymbol{U} \rangle$ ($\boldsymbol{G}$ – fuzzy goal, $\boldsymbol{C}$ – fuzzy constraints, $\boldsymbol{D}$ – fuzzy decision, $\boldsymbol{U}$ – set of decisions). For a given n-dimensional space of states $\mathbf{X} = \{x_1, \dots x_n\}$ and m-dimensional space of controls $\mathbf{U} = \{u_1, \dots u_m\}$ the fuzzy goal is defined as a fuzzy set $\boldsymbol{G} \subseteq \boldsymbol{U}$ with the membership function μ_G:

$$\mu_G : \boldsymbol{X} \times \boldsymbol{U} \to [0, 1] \in \boldsymbol{R} \tag{3}$$

and the fuzzy constraint as a fuzzy set $\boldsymbol{C} \subseteq \boldsymbol{U}$ with the membership function μ_C:

$$\mu_C : \boldsymbol{X} \times \boldsymbol{U} \to [0, 1] \in \boldsymbol{R} \tag{4}$$

If a decision is made in a fuzzy environment, i.e. with a constraint $\boldsymbol{C}$ and goal $\boldsymbol{G}$, described, respectively, by membership functions $\mu_C(x)$ and $\mu_G(x)$, the fuzzy decision $\boldsymbol{D}$ is determined from this relationship:

$$\mu_D(x) = \min_{x \in X}(\mu_G(x), \mu_C(x)) \tag{5}$$

The control process consists in selecting controls u with imposed constraints $\mu_C(x)$, with goals $\mu_G(x)$ imposed on the states x in subsequent control stages. As a quality indicator of the multistage decision making (control) process for k control stages, this fuzzy decision is adopted:

$$D\left(x_{t_0}\right) = C^0 * G^1 * C^1 * G^2 * C^{k-1} * G^k \tag{6}$$

described by the membership functions:

$$\mu_D\left(u_{t_0}, \dots, u_{t_{k-1}} \,\middle|\, x_{t_0}\right) = \mu_{C0}\left(u_{t_0}\right) * \mu_{G1}\left(x_{t_1}\right) * \dots * \mu_{Ck-1}\left(u_{t_{k-1}}\right) * \mu_{Gk}\left(x_{t_k}\right) \tag{7}$$

The problem of multistage control in a fuzzy environment is then formulated as follows:

$$\mu_D\left(u^*_{t_0}, \dots, u^*_{t_{k-1}} \,\middle|\, x_{t_0}\right) = \max\left(\mu_D\left(u_{t_0}, \dots, u_{t_{k-1}} \middle| x_{t_0}\right)\right) \tag{8}$$

The optimal strategy, consequently, has the form of this series of controls u^*:

$$u^* = \left(u^*_{t_0}, u^*_{t_1}, \dots, u^*_{t_{k-1}}\right) \tag{9}$$

The fuzzy goal and fuzzy constraints of fuzzy sets described by their respective membership functions are proposed:

- goal: safe distance of passing an object (another ship, navigational danger);
- constraint 1: possibly small “losses of distance” (shift of the original trajectory);
- constraint 2: noticeably manoeuvre (i.e. visible course alteration).

To avoid the determination of trajectories, where multiple manoeuvres occur, the additional fuzzy constraint is formulated: constraint 3 – small number of manoeuvres, which is also described by the corresponding membership function.

For the safe ship trajectory determination the Dijkstra algorithm has been used [13].

The research

Our research has been aimed at comparing the effectiveness of selected algorithms for ship’s safe trajectory determination in encounter situations in a restricted area. The scenario includes moving objects (vessels), nearby land and other stationary navigational dangers (Fig. 1).

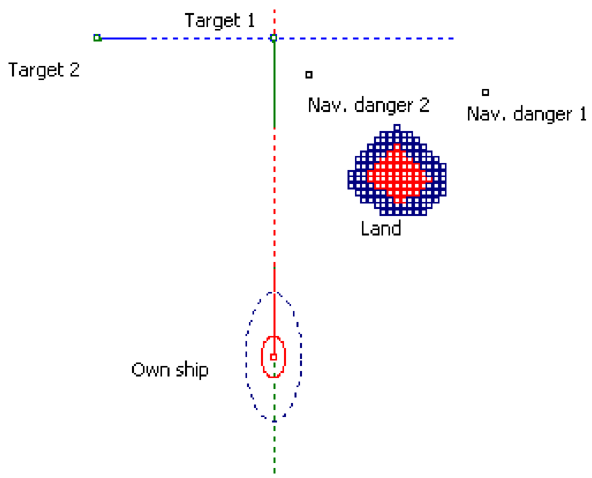

Fig. 1. A scenario of a ship encounter situation in a restricted area

We have assumed that own ship and two targets included in the scenario are of the same type (Table 1).

The algorithm multistage control in a fuzzy environment has been examined for a number of variants of goals and constraints and the corresponding criteria, divided into two main variants:

1) own ship described by a fuzzy domain; target ships described by their contours (ship waterline);
2) own ship described by its contour (ship waterline); targets described by their fuzzy domains.

It is also assumed that the ship fuzzy domain shapes are elliptical. Each domain is described by their minimum and maximum boundary (Table 2).

Table 1. Ship model (based on [10])

Ship model	**LO-RO ship**
Length overall (L_c) [m]	174.0
Breadth (B) [m]	23.0
Draft forward (D_A)	7.5
Speed over water (SOW) [w]	16.3

Table 2. Domain boundary dimensions of LO-RO ship (based on [10])

Domain boundary	Length	Width
minimum (fuzzy)	1200 [m]	675 [m]
maximum (fuzzy)	3670 [m]	1595 [m]

For the simulated coastlines and navigational dangers, the constant safety zones (domains) adopted are respectively: an area up to 500 m along the land and an area up to 200 m around a navigational danger.

For the determination of fuzzy constraints, we have assumed the maximum shift of the original trajectory (constraint 1), the minimum and maximum values of visible course alteration (constraint 2), and admissible (maximum) number of manoeuvres for trajectory planning (constraint 3).

The results

The simulation research has been carried out for safe trajectory determination with the use of multi-step control method. The research has aimed at comparing the effectiveness of selected algorithms for ship's safe trajectory determination in encounter situations in a restricted area. The worked out solutions have been analyzed in respect to safety and the time of finding these solutions, essential for their application in the real conditions. The research has made use of computer simulation, based on the developed scenario of a navigational situation. The scenario includes moving objects (vessels), nearby land and other stationary navigational dangers (Fig. 1).

Variant 1: The own ship fuzzy domain is assumed as the safety criterion. The geometric dimensions of target ships (contours) are considered. For the coastline and navigational dangers the constant safety zones (domains) adopted are respectively: an area up to 500 m along the land and an area up to 200 m around the navigational danger. Figure 2 shows the determined safe trajectories without and with restrictions (constraints) on the number of own ship manoeuvres – fuzzy criterion: small number of manoeuvres performed by own ship: 1) without restrictions; 2) to 20 (maximum); 3) to 7 (maximum).

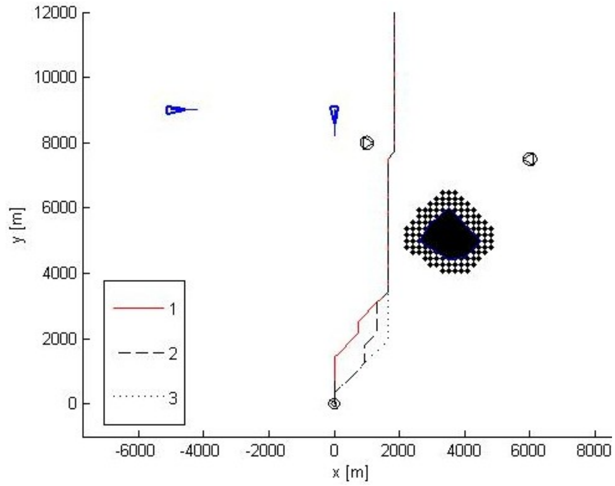

Fig. 2. Own ship trajectories in encounter situations – variant 1: 1) without restrictions on the number of manoeuvres performed by own ship; 2) to 20 (maximum); 3) to 7 (maximum)

Variant 2: In this case the fuzzy domains of target ships are assumed as the safety criterion. Own ship is represented by its contour. For the coastline and navigational dangers the constant safety zones (domains) are determined as in variant 1. Figure 3 shows the determined safe trajectories without and with restriction (constraints) on the number of own ship manoeuvres – fuzzy criterion: small number of manoeuvres performed by own ship: 1) without restrictions; 2) to 20 (maximum); 3) to 7 (maximum).

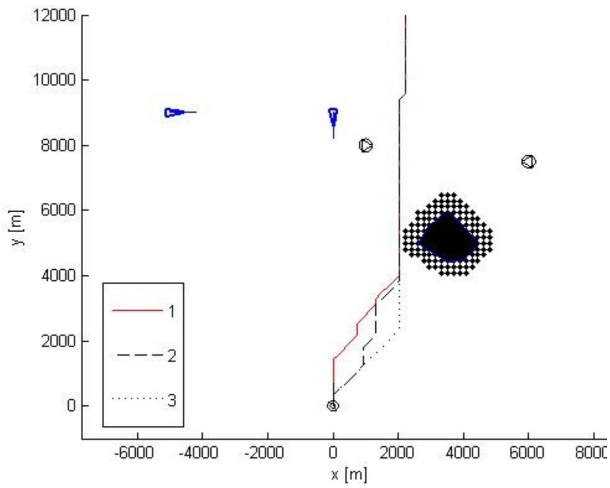

Fig. 3. Own ship trajectories in ship encounter situations – variant 2: 1) without restrictions on the number of manoeuvres performed by own ship; 2) to 20 (maximum); 3) to 7 (maximum)

Such an approach means the definition of fuzzy domains for all encountered ships should be defined. In this case, the solution might be the assignment of the ships' domains, proposed in the

Table 3. Characteristics of determined ships trajectories – variant 1

Trajectory	No. of manoeuvres	Min. distance target 1 [m]	Min. distance target 2 [m]	Min. distance danger 1 [m]	Min. distance danger 2 [m]	Min. distance to land [m]	Shift [m]	Computation time [s]
1	11	1667	1759	4148	815	870	1852	0.229
2	9	1667	1759	4148	815	870	1852	0.274
3	4	1667	1759	4148	815	870	1852	0.267

Table 4. Characteristics of determined ships trajectories – variant 2

Trajectory	No. of manoeuvres	Min. distance target 1 [m]	Min. distance target 2 [m]	Min. distance danger 1 [m]	Min. distance danger 2 [m]	Min. distance to land [m]	Shift [m]	Computation time [s]
1	15	1926	1963	3945	1037	500	2222	0.155
2	11	2037	1963	3945	1037	500	2222	0.174
3	4	2037	1963	3945	1037	500	2222	0.173

literature. This method, even though raising some doubts, gives more possibilities for the own ship trajectory determination.

Analysis of the results

Detailed results of the simulations are given in tables 3 (variant 1) and 4 (variant 2).

Variant 1. The introduction of an additional riterion for a small number of manoeuvres results in a significant reduction in the number of manoeuvres to perform, and thus affects the routing. It should be recognised as important from the viewpoint of the navigator steering the ship. In the analysed ship encounter situation no change of passing distance is observed which seems to be a particular case. The introduction of an additional criterion has not resulted in a significant extension of the calculation time.

Variant 2. Similarly to variant 1, the introduction of an additional criterion for a small number of manoeuvres has resulted in a reduction in the number of manoeuvres in the calculated trajectories. Minor changes in passing distances of ship No. 1 have been observed. The introduction of an additional criterion has not resulted in a significant extension of the calculation time (as in option 1).

In option 2 trajectory calculations have been observed shorter computation times. The values of computation times for each variant allow to draw conclusions on their possible use in real conditions (on-line) for solving more complex navigational situations as well.

Conclusions

This paper presents the problem of determining a safe trajectory for the ship in case of a meeting in the restricted area. Different variants and options are considered to optimize the ship trajectory with the use of ship fuzzy domain criterion. In order to reduce the number of manoeuvres, an additional fuzzy criterion was introduced – criterion of a small number of manoeuvres. Restricted area characteristics – land and navigational dangers – are taken into account.

Simulation research has been carried out for the selected ship encounter scenario. The introduction of an additional criterion has resulted in a significant reduction in the number of manoeuvres under navigational safety conditions (in compliance with the safe navigation conditions). The recorded calculation times confirm the applicability of the proposed methods for determining a safe trajectory in real conditions (on-line) on ships for solving more complex navigation situations.

Both variant 1 – own ship fuzzy domain and contours of target ships – and variant 2 – the own ship contour and domains of target ships – are possible to use. Simpler and more reasonable seems to be the defining of own ship fuzzy domain. The second variant gives more flexibility for own ship trajectory planning (calculations), but it requires the defining of target ship domains.

We are planning to carry out research for other, more complex encounter scenarios in restricted waters, as well as taking into account changes of path prediction parameters, for instance the determination and location of graph nodes or subsequent graph nodes in the path.

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