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MODELS OF SHIP MOVEMENT CONTROL DECISION PROCESSES IN THE VESSEL COMMUNICATIONS AND CO-OPERATION SYSTEM

The article presents models of decision processes taking place in the control of ship movement in an open area. The method of multi-stage control in a fuzzy environment has been used for the determination of a safe trajectory of ship movement. Suitable decision procedures have been developed and implemented in the Vessel Communications and Co-Operation System.

MODELE PROCESÓW DECYZYJNYCH STEROWANIA RUCHEM STATKU W SYSTEMIE KOMUNIKACJI I KOOPERACJI STATKÓW

W artykule przedstawiono modele procesów decyzyjnych w sterowaniu ruchem statku na akwenie otwartym. Do wyznaczania trajektorii bezpiecznej ruchu statku w sytuacjach kolizyjnych zastosowano metodę sterowania wieloetapowego w otoczeniu rozmytym. Opracowano odpowiednie procedury decyzyjne, które zaimplementowano w systemie komunikacji i kooperacji statków.

1. INTRODUCTION

Enhancing the effectiveness and safety in marine transport calls for fast exchange of information and coordination of actions taken by those who supervise and those who participate in the traffic. Information exchange should cover currently performed actions, in certain cases also planned actions. This will make it possible to coordinate actions, and in the case of contradictory goals, a compromise will be reached.

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The system of communication and cooperation of ships, proposed in the work [8], is part of intelligent transport systems. It is implemented in the multi-agent technology. One of its aims is to ensure the safety of navigation through planning safe trajectories of ship movement, and the control of ship movement along a determined trajectory.

The planning of ship movement trajectory may cover various time ranges: planning of the whole voyage by determining a climatic route accounting for weather changes during the voyage and planning a safe ship movement trajectory to prevent and avoid collisions. In both cases of trajectory determination it is purposeful to apply criteria accepted by the human being.

The problems of planning a safe trajectory of ship movement and its control aimed at collision prevention and avoidance are discussed in this article.

2. MODELS OF DECISION PROCESSES OF SHIP MOVEMENT CONTROL

The determined ship movement trajectory has to satisfy the conditions of admissibility and rationality. Such a trajectory is to ensure safe steering of the ship, taking into account economic aspects resulting from the ship's transport task. At the same time attempts are made to take into account the procedures and patterns of inference of the human being. These can be described by decision process models assuming two approaches: descriptive and prescriptive (normative) [6].

The control in the descriptive model is based on the knowledge of input values to be chosen in order to obtain desired output values. In the case of a sea-going ship control, the controlled process is that of ship movement along a specific trajectory. Depending on how detailed control level is assumed, the output x can be ship's present position, course, speed, rudder or engine settings, while the input – respectively – the chosen values of course, rudder, or engine settings. For example, own ship's course can be determined is such a way that passing another ship will be at a pre-set distance (CPA_L). Another method [7, 8, 9] consists in defining a trajectory parallel to the original one so that the closest point of approach (CPA_L) is maintained. In both cases control can be executed with classical controllers or fuzzy controllers.

The prescriptive (normative) approach is based on the knowledge of a model determining the output (effect) as the function of input (cause). In this method a conventional or non-fuzzy optimising algorithm is used for the optimal control of the process.

The choice and form of goals and constraints is essential for a decision taken – i.e. which trajectory to choose. The navigator, planning a manoeuvre, formulates the goal, uses specific criteria and complies with the existing constraints. The basic criteria are those directly resulting from the regulations in force and the criteria for the assessment of a navigational situation.

The criteria directly resulting from the relevant regulations can be of deterministic or descriptive character, considered in terms of fuzziness. The former group of criteria includes the degree of privileges (good visibility conditions) and the criterion of the right of way for ships on starboard side (with the same privilege in good visibility conditions).

The criteria used for the assessment of navigational situation safety are definitely more difficult to interpret and, therefore, to use. These criteria refer to navigator's knowledge, skills and experience as well as the principles of good sea practice. Some of these criteria are as follows:

– criteria for safe passing, overtaking and course crossing,
– criterion of clear and visible course alteration,
– criterion of timely manoeuvre.

The application of the criteria requires the introduction of quantitative and qualitative measures and indicators. These are, among others, the closest point of approach (*CPA*), time to the closest point of approach (*TCPA*), indicators of safety / danger level, ship domain or ship fuzzy domain. The above indicators are defined most often on the basis of navigators' knowledge and experience, but they are also based on analytical formulas, describing the actual phenomena and relationships.

Among the criteria taking into account the economic aspect in choosing the ship movement trajectory, those frequently mentioned are the loss of way, time loss and fuel consumption.

The determination of the ship trajectory consists in specifying the course and speed or trajectory and speed of own ship, so as to ensure safe passing of encountered objects. The problem can be formulated as a single- or multi-stage optimisation.

In the case of single-stage optimisation, most often the problem to be solved is, for the assumed criterion, to determine optimal course Ψ and speed V of own ship (optimisation of the speed components V_x and V_y) or a trajectory parallel to the original trajectory by the linear programming method. The above problem can also be formulated as a non-linear programming problem.

Multi-stage control consists in the choice, among those determinable, the best control series in relation to the assumed criterion for control quality assessment. The task may require the determination of the optimal trajectory through defining ship's turning points and headings at the sections defined by these points or rudder settings and/or engine settings at chosen times. In the classical approach the deterministic form of these elements is assumed. Problems of this type are solved by dynamic optimisation methods.

The navigators making a decision in the ship movement control process, to a lesser or greater degree, rely on approximate values, apply approximate models of objects and approximate constraints and goals. They often use non-crisp /fuzzy/ concepts, such as "safe distance", "dangerous distance", "safe speed", "visible course alteration", "small loss of way". Navigators seek a compromise between contradictory goals, for instance between maintaining "safe distance" to the target ship on the one hand, and "small loss of way" on the other hand. At the same time, they allow certain deviations from strictly set conditions. Thus, a navigator may accept "slightly shorter" distance to the target ship than the pre-set distance ensuring safe passing of the target ship for the sake of lower loss of way caused by a necessary preventive (collision avoiding) manoeuvre. Then the decision problem comes down to one or more optimisation problems with imprecisely defined goals and constraints. One of the methods which takes into account such inaccuracies is the multi-stage control method in a fuzzy environment.

3. MULTI-STAGE CONTROL IN A FUZZY ENVIRONMENT

The fuzzy environment is defined as the ordered four [1]:

$$\langle G, C, D, U \rangle \tag{1}$$

where: ***G*** – fuzzy goal,

C – fuzzy constraints,

D – fuzzy decision,

U – set of decisions.

The fuzzy goal is defined as a fuzzy set $G \subseteq U$ whose membership function μ_G:

$$\mu_G : X \times U \rightarrow [0, 1] \in R \tag{2}$$

whilst the fuzzy constraint is defined as the fuzzy set $C \subseteq U$ with the membership function μ_C:

$$\mu_C : X \times U \rightarrow [0, 1] \in R \tag{3}$$

When a decision is to be made in a fuzzy environment, i.e. with the goal G and constraint C, described by respective membership functions μG(x) and μC(x), the fuzzy decision D is determined from this relationship:

$$\mu_D(x) = \mu_G(x) * \mu_C(x) \tag{4}$$

where (*) is the aggregation of fuzzy sets. There are several types of fuzzy decisions. One of most used is an operator of minimum type:

$$\mu_D(x) = \mu_G(x) \wedge \mu_C(x) = \min(\mu_G(x), \mu_C(x)) \tag{5}$$

It is assumed that an optimal decision is a maximizing decision (4), i.e.:

$$\mu_D(x^*) = \max_{x \in X}(\mu_D(x)) \tag{6}$$

This also refers to a situation where many (n) goals and many (m) constraints exist. Then the fuzzy decision is defined as:

$$\begin{aligned} \mu_D(x) = \mu_{G1}(x) * \mu_{G2}(x) * \ldots\ldots * \mu_{Gn}(x) * \\ * \mu_{C1}(x) * \mu_{C2}(x) * \ldots\ldots * \mu_{Cm}(x) \end{aligned} \tag{7}$$

where: n – number of goals,

m – number of constraints.

The control process for the state space $X = \{x_1, \dots x_n\}$ and control set $U = \{u_1, \dots u_m\}$ consists in the selection of control variables u_j under constraints $\mu_{Cj}(x)$ with the goals $\mu_{Gi}(x)$ imposed on the states x_i in subsequent stages of control.

The following fuzzy decision (D) is taken as a quality criterion of multi-stage decision-making process (control):

$$D(x_0) = C^0 * G^1 * C^1 * G^2 * C^{P-1} * G^P \tag{8}$$

where:

P – number of control stages,
C^i – constraint at i-th stage of control,
G^i – goal at i-th stage of control,
x_0 – initial state of the process.

4. RESEARCH

The following criteria have been considered while determining a safe trajectory of ship movement in an encounter situation, using the method of multi-stage control in a fuzzy environment:

- criteria resulting from the regulations,
- fuzzy closest point of approach (CPA_{LF}),
- recommended (visible) course alteration (CR_{RF}),
- deviation from the trajectory (small loss of way) (DT_{SF}),

The case for good visibility conditions was considered. The functions of fuzzy sets membership, describing the above criteria, were defined: fuzzy closest point of approach (μ_{CPALF}), recommended (visible) course alteration (μ_{CRRF}) and deviation from the trajectory (small loss of way) (μ_{DTSF}):

$$\mu_{CPALF}(d) = \begin{cases} 0 & for \quad d < CPA_{L\min} \\ \dfrac{d - CPA_{L\min}}{CPA_{L\max} - CPA_{L\min}} & for \quad CPA_{L\min} \le d \le CPA_{L\max} \\ 1 & for \quad d > CPA_{L\max} \end{cases} \tag{9}$$

where:

d– distance from the target ship,
CPA_{Lmin}, CPA_{Lmax} – minimum and maximum closest points of approach, respectively,

$$\mu_{CRRF}(\Delta\mu_{CRRF}) = \begin{cases} 1 & for \quad \Delta\Psi = 0 \\ \dfrac{\Delta\Psi - \Delta\Psi_{min}}{\Delta\Psi_{RL} - \Delta\Psi_{min}} & for \quad \Delta\Psi_{min} \le \Delta\Psi < \Delta\Psi_{RL} \\ 1 & for \quad \Delta\Psi_{RL} \le \Delta\Psi \le \Delta\Psi_{RH} \\ 1 - \dfrac{\Delta\Psi - \Delta\Psi_{RH}}{\Delta\Psi_{RH} - \Delta\Psi_{max}} & for \quad \Delta\Psi_{RH} < \Delta\Psi \le \Delta\Psi_{max} \\ 0 & in\ another\ case \end{cases} \tag{10}$$

where:
$\Delta\Psi$ – course alteration,
$\Delta\Psi_{min}$ – minimum course alteration,
$\Delta\Psi_{RL}$ – recommended lower boundary of course alteration,
$\Delta\Psi_{RH}$ – recommended upper boundary of course alteration,
$\Delta\Psi_{max}$ – maximum acceptable course alteration.

$$\mu_{DTSF}(y_d) = \begin{cases} 1 & for\ y_d < y_{min} \\ 1 - \dfrac{y_d - y_{min}}{y_{max} - y_{min}} & for\ y_{min} \le y_d \le y_{max} \\ 0 & for\ y_d > y_{max} \end{cases} \qquad (11)$$

where:
y_{min}, y_{max} – respectively, the values of minimum and maximum deviations from the original trajectory acceptable by the navigators.

The aggregation operator of the minimum type (5) was used for the determination of control quality indicator. The optimal ship control in the sense of a fixed control quality indicator (8) is determined using the Bellman's optimisation principle. This defines the basic feature of the optimal strategy that says that, regardless of the initial state and decision, the other decisions have to make up optimal strategies from the point of view of the state resulting from the first decision. The above problem can be solved by various methods. The problem of determining the optimal ship trajectory may be effectively solved by the graph method. The properties of the directed graph are utilized. The graph's edges are oriented towards and the arrow indicates the direction of movement or sequence of choice. One of the most effective algorithms proposed for the determination of the shortest path between a specific pair of vertexes is Dijkstra's algorithm [3].

The situation examined was the encounter of ships in an open sea area covered by the system of ship communication and cooperation. The ships' dynamics was simulated by means of the verified analytical model of the m/f J.Śniadecki [4, 5]. The regulations in force [2] for good visibility conditions have been taken into consideration.

Encounters of ships on various headings were simulated. According to the regulations, in the presented collision situation the ship A is obliged to give way to the ship B. Obeying the regulations and following good sea practice the ship A performs a preventive manoeuvre. Navigating in the open sea, the ships, having performed a collision-avoiding manoeuvre often return to their original course.

Having analysed a navigational situation and recognizing a collision situation, the ship A sends a message to the ship B informing it has recognized a collision situation and confirms it is obliged to make a collision avoiding manoeuvre. After it manoeuvres to avoid a collision, the ship A returns to its original trajectory. The ship A sends information on the type of the planned manoeuvre and when it will be started. The ship also gives the points of its movement trajectory. The ship B acknowledges the information on the planned actions of the ship A. The ship B analyses the manoeuvre to be performed by the ship A and sends acknowledgement. The ship A starts the manoeuvre – sails following the determined safe trajectory.

In order to implement the determined ship movement trajectory the authors used a modified cascade fuzzy controller based on the model presented in [7].

Figures 1÷4 illustrate both ships' trajectories, the distances between the ships, courses of the ship A and headings on the ship B in various encounter situations.

The manoeuvres were properly performed, in compliance with the regulations, in a timely and clear-cut manner. In each of the examined cases the ship A began its collision-preventing manoeuvre at a distance not less than 3.5 Nm. The course was altered in a way noticeable for the ship B. The ships pass each other at a safe distance (admissible range of the closest approach). The manoeuvres were executed so that the ship B found itself early of the ship A. This reflects common practice of navigators.

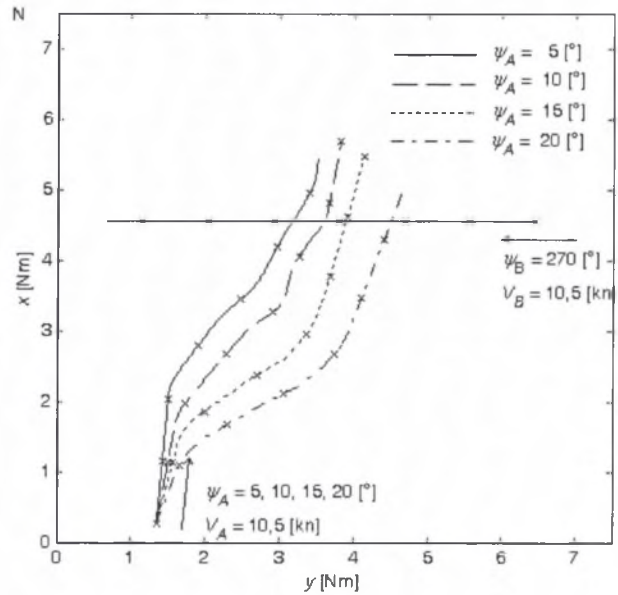

Fig.1. Ships' trajectories in various encounter situations; positions (x) on 300 [s] time intervals

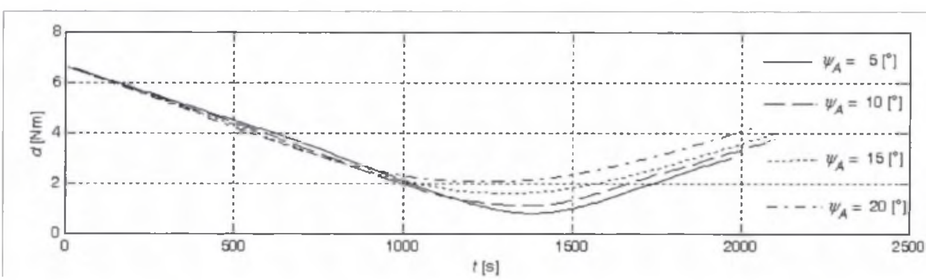

Fig.2. Distances between ships in various encounter situations

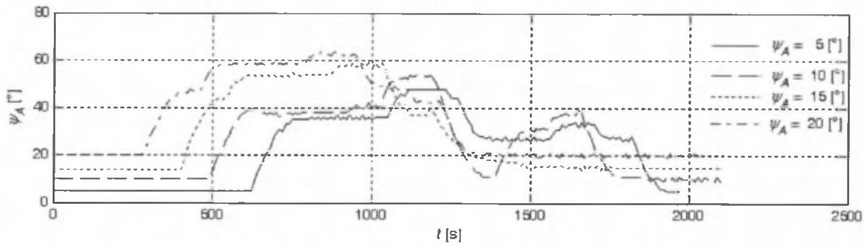

Fig.3. Courses of the ship A in various encounter situations

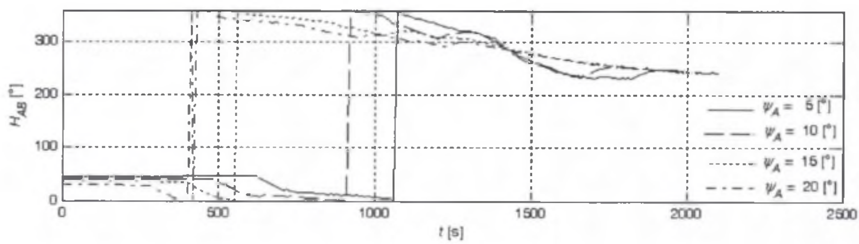

Fig.4. Headings on ship B in various encounter situations

During the manoeuvres, the ships followed standard procedures typical of the communication and cooperation of vessels.

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