MODELLING OF NAVIGATORS’ BEHAVIOUR
IN RESTRICTED AREA NAVIGATION

Pietrzykowski Z.
Maritime University of Szczecin, Institute of Marine Navigation, Szczecin, Poland

Abstract: Modelling of decision making processes taking place in the mind of a navigator steering a ship in a restricted area is a specific problem dealt with by marine traffic engineering. Models of navigators’ behaviour are used for designing autonomous systems of ship movement control and simulation research on ship movement. This article presents the problem of planning a trajectory of a ship sailing in a restricted area formulated as an optimization problem – multi-stage control in a fuzzy environment. Its goals and constraints have been defined by means of linguistic terms. The theory of fuzzy sets has been used for the purpose. Some navigational situations in a fairway, i.e. a restricted area, have been considered. The author’s model of navigator’s decision making processes has been used in simulation research. Finally, the results have been analyzed and some conclusions formulated.

1. Introduction

The major task of a navigator steering a sea-going ship is to reach the destination according to ship owner’s instructions. On the way, the navigator has to comply with the principles of safe navigation, regulations in force, instructions and recommendations of VTS operators. Sea-going ship movement control continuously requires decisions to be made. These decisions result from the tasks a given ship performs – carriage of cargo and people.

The amount of available information, constantly increasing, and a growing complexity of technical systems in use make information management and associated decision making, particularly in complicated and difficult situations, such as emergencies, outstandingly difficult for decision makers. One way of tackling this problem is to develop decision support systems on various management levels. Solutions determined by such systems should take into account the regulations in force, ensure safe manoeuvres and be rational. This means, inter alia, the application of criteria used by and acceptable to the human being. This is essential if the system is to be reliable and have practical use. The implementation of such systems is based on an analysis of decision making processes taking place in sea-going vessel movement control.
2. The restricted area

The restricted area is a water area where the wave system, generated by a ship proceeding at full speed, is disturbed. In a restricted area the navigator has no possibility to choose the route freely and has to comply with safety rules, accounting for local conditions (one of the three dimensions determining the ship’s distance to other objects is restricted). Manoeuvres in a restricted area are related with the type of waterway the ship is in [2]. The following sea water areas are distinguished: fairway: straight section, bend; port entrance; anchorage; turning area; port basin with quays; lock.

Manoeuvres performed within the above areas are as follows: passing along a fairway, anchoring, turning, berthing/unberthing, entering/leaving a lock. These manoeuvres may be performed by ships on their own or with the help of tugs. The performance of the manoeuvre and the choice of a given trajectory of ship movement depend on the area itself, the ship, prevailing hydro-meteorological conditions as well as the qualifications (knowledge, experience, skills) of the navigator steering the ship.

A ship passing along a fairway has to take into account vessel traffic and hydrographic dangers within the area (area shape, forms of sea bottom shape, hydro-technical structures, wrecks, etc.). In ship encounter situations the following manoeuvres are performed: passing, overtaking, crossing, following another ship, passing a mooring or anchoring ship.

These have to account for the regulations in force, specific characteristics of the area and the present traffic situation. Safe performance of these manoeuvres calls for the determination of ship movement trajectory with the existing constraints being taken into account [4].

Passing and overtaking manoeuvres require the cooperation of the navigators on the ships involved. During these manoeuvres the trajectory to be chosen has to assure safe distances from the ship being passed / overtaken (goal) and from the fairway boundary (constraint). Besides, it is necessary to take into account the specific character of particular manoeuvres due to different time of their execution.

The manoeuvres such as crossing and following another ship are connected with the setting of the proper speed by the ship which is to give way (crossing), or adjusting own ship’s speed to the speed of the other ship (following) in order to maintain safe distance to the other ship.

Passing a mooring or anchoring ship also requires safe distance to be kept so that damage is not caused, e.g. due to breaking mooring lines / anchor chain or rolling the ship being passed (goal), while safe distance to the area limit is maintained.
3. Ship movement control process

While steering their ships, navigators often use such fuzzy terms as “safe distance”, “dangerous distance”, “safe speed”, “distinct course alteration”, “small loss of way”. Making decisions they seek a compromise between contradictory goals, e.g. keeping “safe distance” from the other ship and “small loss of way”. Navigators, however, allow for certain deviations from strictly set conditions. This means, for instance, that “slightly smaller” distance to the other ship than the preset one will be accepted as it still provides for safe passing of the other ship and at the same time reduces the loss of way caused by the necessitated collision-avoiding manoeuvre.

The representation and processing of these imprecise terms and information can be realized by the theory of fuzzy sets. Its applicability and usefulness is confirmed by practical implementations of systems and equipment fitted with control systems based on fuzzy logic. This also refers to marine navigation.

The actual process of ship being steered by the navigator can be considered as a single- or multi-stage control. When we take into account the inaccuracies (imprecise assessments) occurring in the ship movement control process, it can be considered as single-stage optimization in a fuzzy environment or multi-stage fuzzy control [3].

4. Multi-stage control in a fuzzy environment

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

$$\langle G, C, D, U \rangle$$

(1)

where:

- G – fuzzy goal,
- C – fuzzy constraints,
- D – fuzzy decision,
- U – set of decisions.

When decisions are made in a fuzzy environment, i.e. with the constraint C and goal G, described, respectively, by membership functions $\mu_C(x)$ and $\mu_G(x)$, the fuzzy decision D is determined on the basis of this relationship:

$$\mu_D(x) = \mu_G(x) \ast \mu_C(x)$$

(2)

where:

- $\mu_C : X \times U \rightarrow [0, 1] \in R$
\( \mu_G : X \times U \to [0, 1] \in R \)

\((*)\) – aggregation of fuzzy sets.

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

\[
\mu_D(x^*) = \max_{x \in X} (\mu_D(x))
\]

for \( x \in X \). It also refers to a situation where many goals and many constraints exist.

The control process for the space of states \( X = \{x_1, \ldots, x_n\} \) and controls \( U = \{u_1, \ldots, u_m\} \) consists in the selection of control variables \( u \) with the imposed constraints \( \mu_C(x) \) and goals \( \mu_G(x) \) laid on states \( x \) in the subsequent control stages.

The quality indicator of the multi-stage decision making process (control) is assumed to be the fuzzy decision

\[
D(x_0) = C^0 \ast G^1 \ast C^1 \ast G^2 \ast C^{p-1} \ast G^p
\]

where:

\( P \) – number of control stages,

\( C^i \) – constraint at the \( i \)-th control stage,

\( G^i \) – goal at the \( i \)-th control stage,

\( x_0 \) – initial stage of the process.

The decision \( D \) is described by respective membership functions:

\[
\mu_D(u_0, \ldots, u_{N-1} \mid x_0) = \mu_{C^p}(u_p) \ast \mu_{G^p}(x_p) \ast \ldots \ast \mu_{C^1}(u_1) \ast \mu_{G^1}(x_1) \ast \mu_{C^0}(u_0)
\]

(5)

The multi-stage control problem is then formulated as follows:

\[
\mu_D(u_0^*, \ldots, u_{N-1}^* \mid x_0) = \max(\mu_D(u_0, \ldots, u_{N-1} \mid x_0))
\]

(6)

Then the optimal strategy is composed of a series of control settings \( u^* \):

\[
u^* = (u_0^*, u_1^*, \ldots, u_{N-1}^*)
\]

(7)

By formulating the problem of ship movement trajectory planning as a problem of multi-stage control in a fuzzy environment we are able to take into account those inaccuracies that result from imprecise criteria used by the navigator while determining a ship movement trajectory.
5. Planning a ship movement trajectory in a restricted area

An open sea area offers the navigator one distinct feature: he can choose the ship’s route at his discretion. Planning a ship movement trajectory on the operational level relates to handling encounter situations in order to safely pass the other ship or ships. Planning a given manoeuvre, the navigator optimizes it to achieve a specific goal according to assumed criteria and accounting for existing constraints. These criteria include:[7]:

- safe passing, overtaking or crossing distance,
- distinct, i.e. noticeable alteration of ship’s course,
- economical aspects: loss of time, loss of way, fuel consumption etc.

Contrary to the open sea, in restricted areas the criterion of the fuzzy closest point of approach CPA cannot be applied [5]. The safe area around the ship (goal) is determined by the ship fuzzy domain, an area around the ship which the navigator should maintain clear of other vessels and objects. The domain shape and size depend on the adopted level of navigational safety, understood as a degree of membership of a navigational situation to the fuzzy set “dangerous navigation” [4, 6]. The ship fuzzy domain $D_{SFD}$ with the heading angle $\angle K$ is described by the membership function $\mu_{DSFK}$ (object – ship, fairway boundary, navigational obstruction – is located on this heading at the distance $d_K$). The ship fuzzy domain $D_{SF}$, described by the membership function $\mu_{DSF}$, represents the fuzzy set “safe navigation”, which is the complement of the set “dangerous navigation”.

Constraints are described by fuzzy sets of a shift in relation to the recommended trajectory $C_{LF}$, distinct and allowable course alteration $C_{WF}$ and, if appropriate, safe distance from a mooring or anchoring ship, $C_{MF}$ and $C_{AF}$; they are described by the respective membership functions: $\mu_{CLF}$, $\mu_{CWF}$, $\mu_{CMF}$ and $\mu_{CAF}$.

The fuzzy decision $D_{DSF}$ is then formulated in this way:

$$\mu_{D_{DSF}}(u_0, ..., u_{N-1} | x_0) = \mu_{DSFK}(d_{K0}) \ast \ast (\mu_{DSFK}(d_{K1}) \ast \ast \mu_{DSFK}(d_{K2}) \ast \ast \mu_{DSFK}(d_{KN}))$$

$$\ast \mu_{CLF}(d_{Z1}) \ast \ast \mu_{CLF}(d_{Z2}) \ast \ast \mu_{CLF}(d_{ZN})$$

$$\ast \mu_{CMF}(d_{M1}) \ast \ast \mu_{CMF}(d_{M2}) \ast \ast \mu_{CMF}(d_{MN})$$

$$\ast \mu_{CAF}(d_{A1}) \ast \ast \mu_{CAF}(d_{A2}) \ast \ast \mu_{CAF}(d_{AN})$$

$$\ast \mu_{CWF}(u_0) \ast \ast \mu_{CWF}(u_1) \ast \ast \mu_{CWF}(u_{N-1})$$

(8)

where:

- $N$ = number of control stages,
- $i$ = $i$-th control stage, $i = 0, 1, 2, ..., N$,
- $u_i$ = own ship’s course at the $i$-th control stage,
- $d_{Ki}$ = own ship’s distance from the other ship at the $i$-th control
stage on the $K$-th heading angle, with $d_{K_i} = d_{K_i}(u_0, \ldots, u_{i-1} | x_0)$.

- $d_{Z_j}$ value of the shift from the original (recommended) trajectory at the $j$-th control stage, with $d_{Z_j} = d_{Z_j}(u_0, \ldots, u_{j-1} | x_0)$.

- $d_{M_i}$ own ship’s distance from a mooring ship at the $i$-th control stage, with $d_{M_i} = d_{M_i}(u_0, \ldots, u_{i-1} | x_0)$.

- $d_{A_i}$ own ship’s distance from an anchoring ship at the $i$-th control stage, with $d_{A_i} = d_{A_i}(u_0, \ldots, u_{i-1} | x_0)$.

- $\mu_{DSF}(d_{K_i})$ membership function of the ship fuzzy domain on the $\angle K$ heading angle at the $i$-th control stage.

- $\mu_{CLF}(d_{Z_i})$ membership function to the set ‘small shift relative to the original trajectory’.

- $\mu_{CMF}(d_{M_i})$ membership function to the set ‘small shift relative to the original trajectory’.

- $\mu_{CAF}(d_{A_i})$ membership function to the set ‘small shift relative to the original trajectory’.

- $\mu_{CWF}(u_i)$ membership function to the set ‘distinct course alteration’ at the $i$-th control stage.

The optimal control problem (6) can then have this form:

$$
\mu_{D_{DSF}}(u_0^*, \ldots, u_{N-1}^* \mid x_0) = \max( \mu_{D_{DSF}}(u_0, \ldots, u_{N-1} \mid x_0) )
$$

(9)

6. Research

The research focused on encounter situations in a restricted area – fairway 200 metres wide. The examined manoeuvres included overtaking, passing and passing a moored ship. The research, consisting of both expert and simulation tests performed by navigators, resulted in determining membership functions of fuzzy sets described in Section 3. The research focused on the assessment of navigational safety in good visibility conditions. The method of multi-stage control in a fuzzy environment was used for the determination of ship movement trajectory. Manoeuvring characteristics were taken into account.

Examples of the results are shown in Figures 1, 2 and 3. The own ship, 95 m long and 18 metres in breadth was proceeding at a speed of 4.1 m/s (8 kn). The target ship of the same size was steaming at 4.1 m/s (8 kn) – passing manoeuvre; and at 2.1 m/s (4 kn) during the overtaking manoeuvre.
The determined trajectories of own ship in open and restricted areas ensure the passing of another ship at a safe distance. They are in compliance with the regulations in force and the principles of good marine practice.
7. Conclusions

The herein presented method of determining a safe trajectory of ship movement allows to take into account the criteria used and accepted by navigators. In the analyzed cases it provides for safe manoeuvres executed in restricted areas.

Further research, in which expert navigators will also be engaged, will verify this method of the ship movement trajectory planning.

The presented method may be used in systems of navigator decision support both on board ships and in land-based vessel traffic service centres, while in the future in automatic ship control systems.

References