A Navigator Decision Support System in Planning a Safe Trajectory

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ABSTRACT

The problem of safe and effective, i.e. economical handling of a sea-going vessel is connected with collision avoidance maneuvers and voyage planning (route planning) of vessels. In both cases various methods and tools are used for analyzing and assessing a navigational situation as well as maneuver planning and execution. Such actions are aimed at building systems of decision support and automatic ship handling. Authors of such systems increasingly make use of the knowledge and experience of expert navigators. Most often the idea comes down to the expert knowledge implementation in chosen tasks that appear in the process of navigation. The paper presents a navigator decision support system used in planning a safe trajectory. The concept of ship fuzzy domain is used in decision process modeling. The problem of determining a safe trajectory was formulated as an optimal control task. The paper presents a model of a decision process, an optimization algorithm and examples of some maneuvers. The system can supplement and extend the potential of ARPA (Automatic Radar Plotting Aids) systems which are in operation on board ships.

1. Introduction

The operation of a sea-going ship covers its use in normal and emergency situations as well as maintenance. Therefore, decisions made on board a ship relate to:

- keeping the ship operational and assuring its safety,
- organizational ad technical work resulting from ship's transport task,
- safe loading of cargo, its securing for voyage,
- safe optimal transfer of cargo and people,
- safe discharge of cargo.

The planning of a safe trajectory is required for safe and optimal transfer of cargo and people– execution of a sea passage. Navigational decisions taken refer to various time ranges:

- weather planning of a voyage which accounts for changing weather conditions during a voyage – strategic decisions,
- ship control (collision prevention and avoidance) – operating decisions.

Tasks of weather voyage planning are in most cases executed by specialized land-based centers, whereas ship's navigation (collision prevention and avoidance) and associated operating decisions totally rest on the navigator who steers the ship.

An increasing volume of available information and growing complexity of shipboard technical systems make the information management and decision making on this basis more difficult. Especially in the case of complicated navigation situations, e.g. damage, it can go beyond the possibilities of decision-makers. One way of finding solutions to this problem is a development of decision support systems at various levels of making decisions.

2. Scope of Making Decisions

A set of navigational decisions comprises maneuvers of altering a course or speed changes, while in dangerous situations the two kinds of maneuvers are used. Actions taken by a ship are determined by several factors:

- COLREGs (1972), i.e. regulations that determine a kind of admissible maneuvers, e.g. altering course to port, turning to port, slowing down, stopping the ship.
- Factors, that will be important for the ‘force’ of a maneuver, e.g. by 15 or 60 degrees, slowing down by reducing speed, stopping the engines or crash stopping, such as:
    - positions of both ships,
    - ships’ speeds,
    - distances between ships,
    - maneuvering abilities of ships,
    - hydrological and meteorological conditions,
    - traffic intensity,
    - type of area etc.

Attempts to identify ship’s behavior due to the COLREGs regulations were made by Cockcroft (Cockcroft, 1972) and Jones (Jones, 1978) and others. They aimed at developing procedures would define the direction of altering course and/or speed which comply with the regulations in force. Cockcroft’s and Jones’ diagrams refer only to an open area and restricted visibility.

In (Lisowski, 1986) basic ship passing situations as recommended by COLREGs are presented as well as the form of logical function Z_j semantic interpretation of legal rules of maneuvering. The work (Lisowski and Smierzchalski, 1995) presents a method of determining safe maneuvers for various courses and speeds of own ship in the form of tables. Safe and collision maneuvers, given respectively, 1 and 0 values, were determined for quantified courses and speeds of the own ship.

Having taken into account the semantic interpretation of legal rules of maneuvering, one can determine a safe maneuver in a particular encounter situation.

3. Situation Assessment Criteria

The analysis and assessment of a navigational situation based on the assumed criteria are critical for the decision-making process. From the information on the present navigational situation, including such data as the type of area, its specific character, encounter situation, regulations applicable in a given situation are selected and prioritized. The decision whether to take action or not is based on the regulations in force and on adequate criteria for an assessment of a navigational situation. When action has to be taken, its kind and range are defined. The following criteria for a navigational situation assessment can be distinguished:

- criteria directly imposed by the regulations,
- closest point of approach CPA_L,
- safety level,
- ship domain,
- ship fuzzy domain.

3.1 CPA Criterion

This widely used criterion for navigational situation assessment is applied in the automatic radar plotting aid (ARPA). It is assumed that the navigator will determine the minimum (limit) distance at which other objects will be passed (CPA_L). If the condition

$$CPA \geq CPA_L \tag{1}$$

is not satisfied, a collision avoidance maneuver has to be made for the ship to clear an object at a safe distance. An additional criterion is the time to closest point of approach (TCPA) – its minimum value $TCPA_L$ is also defined by the navigator. If the condition (1) is not satisfied

$$TCPA \geq TCPA_L \tag{2}$$

a collision avoidance maneuver has to be immediately carried out so that the ships will pass each other at a safe distance. There are also criteria taking into account both CPA_L and $TCPA_L$ at the same time.

3.2 Ship's Domain Criterion

When navigating a ship, the navigator tends to maintain a certain area around it clear of other navigational objects. Authors most often divide the area around the ship into the safe and dangerous zones. According to Goodwin (Goodwin, 1975), the ship's domain is an area around the vessel that the navigator wants to keep clear of other objects. Any entry into the dangerous zone – ship's domain – is interpreted as a threat to navigational safety. Authors propose two- and three-dimensional domains. In the former case the domains describe an area around the ship. The shapes of two-dimensional domains can be circular, rectangular, elliptical, polygon, or more complex figures. The domain shape and size depend on a number of factors, which makes the determination of the domain difficult. The human factor, naturally, is of paramount importance.

3.3 Ship Fuzzy Domain Criterion

A hypothesis has been made in (Zhao and Wang, 1993) that there is a ”fuzzy boundary” of a ship domain. Only when the navigator foresees that the area within that boundary will be crossed, he will be forced to take action. The concept of ship fuzzy domain (Fig. 1) extends and generalizes both the terms of ship domain and fuzzy boundary of ship domain (Pietrzykowski, 1999, 2002):

ship fuzzy domain – an area around the ship which should be maintained free from other craft and objects by the navigator; its shape and size depend on the preset level of navigational safety, understood as the degree of membership of a navigational situation to the fuzzy set "safe navigation" ("dangerous navigation").

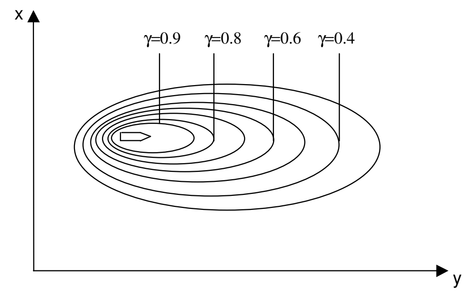

Figure :. Fuzzy domain; its boundaries for various values of navigational safety level $\gamma(\gamma\in<0, 1>)$; $\gamma=0$ – very safe situation; $\gamma=1$ – very dangerous situation

Depending on a situation, the navigator assumes the minimum allowed level of safety γ and/or searches for a compromise between the above criterion and other criteria of maneuvers assessment, e.g. loss of way.

4. Criteria for Maneuvers Assessment in Ship Control Process

The optimal control of a multi-dimensional non-linear dynamic object, such as a ship is, consists in choosing from among definable series of settings, the best ones in terms of the assumed criterion of control quality assessment. The essential factors in this respect are the range and accuracy of information on the navigational situation as well as the chosen process model. This task may refer to the determination of an optimal trajectory by defining ship's turning points and course angles at sections limited by those points or by defining rudder and–or engine settings at chosen times.

4.1 Optimal control

The control quality indicator J is mostly the time or distance function, while in the case of multi-criterion optimization the additional indicators are the closest point of approach or the time to the closest point of approach, fuel consumption etc

$$J(x^*(t), u^*(t), t) = \min_{U_0,\, X_0} \int_{t_0}^{t_k} f_0(x(t), u(t), t)\,dt \tag{3}$$

where:

f_0 – function of momentary losses,

$u(t) \in U_0$ – set of admissible settings,

$x(t) \in X_0$ – admissible space of trajectories,

$u^*(t)$ – optimal setting,

$x^*(t)$ – optimal trajectory.

The admissible space of trajectories is limited by the introduction of an area around the ship, which has to remain clear of other objects: e.g. a circle with the radius CPA_L or a ship domain. It is possible to introduce additional constraints, e.g. minimum or maximum alteration of a ship's course etc. The above problem can be solved by dynamic programming methods, the branch-and bound method or using the theory of graphs.

4.2 Ship Control in a Fuzzy Environment

A method of ship control in a fuzzy environment offers an alternative for a problem defined in section 4.1. The fuzzy environment means goals and constraints presented in a non-crisp form with the use of fuzzy sets theory (Bellman and Zadeh, 1970), (Kacprzyk, 2001). One example is the safe maneuver criterion – ship fuzzy domain, described by the membership function $\mu_{DSF}\angle K_i(d)$:

$$\mu_{DSF\_\angle Ki}(d) = \begin{cases} 0 & for\ d < d_{\min}(\angle K_i) \\ \dfrac{d - d_{\min}(\angle K_i)}{d_{\max}(\angle K_i) - d_{\min}(\angle K_i)} & for\ d_{\min}(\angle K_i) \le d \le d_{\max}(\angle K_i) \\ 1 & for\ d > d_{\max}(\angle K_i) \end{cases} \tag{5}$$

where:
d – distance to the other (target) ship
$\angle Ki$ – heading angle on the other ship; $i = 0, 1,...,180$ [°]
$\mu_{DSF\_\angle Ki}(d)$ – member ship function of distance on the heading angle $\angle Ki$ of the ship's fuzzy domain,
$d_{min}(\angle Ki)$ – distance from the boundary of domain D_{Smin} on the heading angle $\angle Ki$,
$d_{max}(\angle Ki)$ – distance from the boundary of domain D_{Smax} on the heading angle $\angle Ki$,

By analogy, a constraint may be a loss of way expressed as a distance of deviation from the original trajectory, described by the membership function μ_{C_LW} :

$$\mu_{C\_LW}(y) = \begin{cases} 0 & for\ y > y_{\max} \\ 1 - \dfrac{y - y_{\min}}{y_{\max} - y_{\min}} & for\ y_{\min} \le y \le y_{\max} \\ 1 & for\ y < y_{\min} \end{cases} \tag{6}$$

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

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

$$D(x_0) = C^0 * G^1 * C^1 * G^2 * C^{P-1} * G^P \tag{7}$$

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,
x_i, – process state at i-th state of control.

The above decision *D* is described by the membership functions:

$$\mu_D(u_0, ..., u_{N-1} \mid x_0) = \mu_{C0}(u_0) * \mu_{G1}(x_1) * ... * \mu_{CP-1}(u_{P-1}) * \mu_{GP}(x_p) \qquad (8)$$

The (multi-stage) task of optimal control is then formulated as follows:

$$\mu_D(u_0^*, ..., u_{N-1}^* \mid x_0) = \max(\mu_D(u_0, ..., u_{N-1} \mid x_0)) \qquad (9)$$

Then, the optimal strategy is made up of a series of settings u^*

$$u^* = (u_0^*, u_1^*, ..., u_{N-1}^*) \qquad (10)$$

The above problem – like in the traditional approach – can be solved by dynamic programming methods, the branch-and bound method or using the theory of graphs.

This approach make possible to describe the decision process in a manner similar to that executed by the human – navigator.

5. Research

The optimal trajectory determination task was performed with the use of the graph method, (Deo, 1980). The CPA_L criterion, ship's domain D_S and the ship's fuzzy domain D_{SF} were used as criteria for the assessment of a navigational situation. To this end an expert research was conducted. The research focused on the assessment of ship encounter situations in open areas in good visibility.

Navigators, captains and watch officers of various sea service and professional experience, participated in the research, in which questionnaires were used. The navigators were told to determine safe distances for various encounters of own ship and target ship one with the parameters similar to those of the m/s Freight. The values of closest point of approach CPA_L, the domains: D_S , D_{Smin} , and D_{Smax} were determined (Fig 2.). On this basis, fuzzy criterion was defined for the maneuvering assessment: ship's fuzzy domain D_{SF}, described by the membership function $\mu_{DSF\angle Ki}(d)$:

The covered distance was taken as a quality indicator for the choice of an optimal trajectory in a control problem solved in a traditional manner.

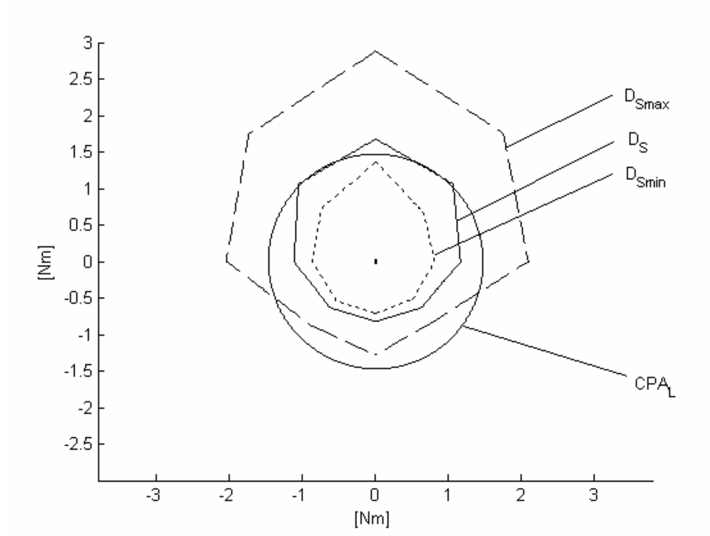

Figure 2: Safe passing distances to another ship according to the closest point of approach (CPA_L) criterion and ship's domains

Fuzzy constraints were taken to account in the case of the control in a fuzzy environment:

- the deviation y from the original trajectory, described by the membership function μ_{C_DT} (6),
- acceptable course change in relation to the original course, described by the membership function μ_{C_CC} (analogously to μ_{C_LW}).

Encounter situations of ships on crossing courses were considered. The collision regulations in force in the conditions of good visibility were taken into account.

A non-linear model of ship's dynamics (Norrbin, 1971) was used for the description of the movement of a ship as a controlled object. The ship's dynamics was modeled for a cargo ship with a capacity of 5427 DWT, length overall 95 [m], beam 18.2 [m] and draft 5.5 [m].

5.1 Optimal Control Execution

The results of the multi-stage control for crisp (non-fuzzy) criteria of navigational safety assessment: closest point of approach and ship's domain – are presented in Figure 3. The maneuvers were performed in an acceptable manner (nearly correct), similar to those carried out in practice.

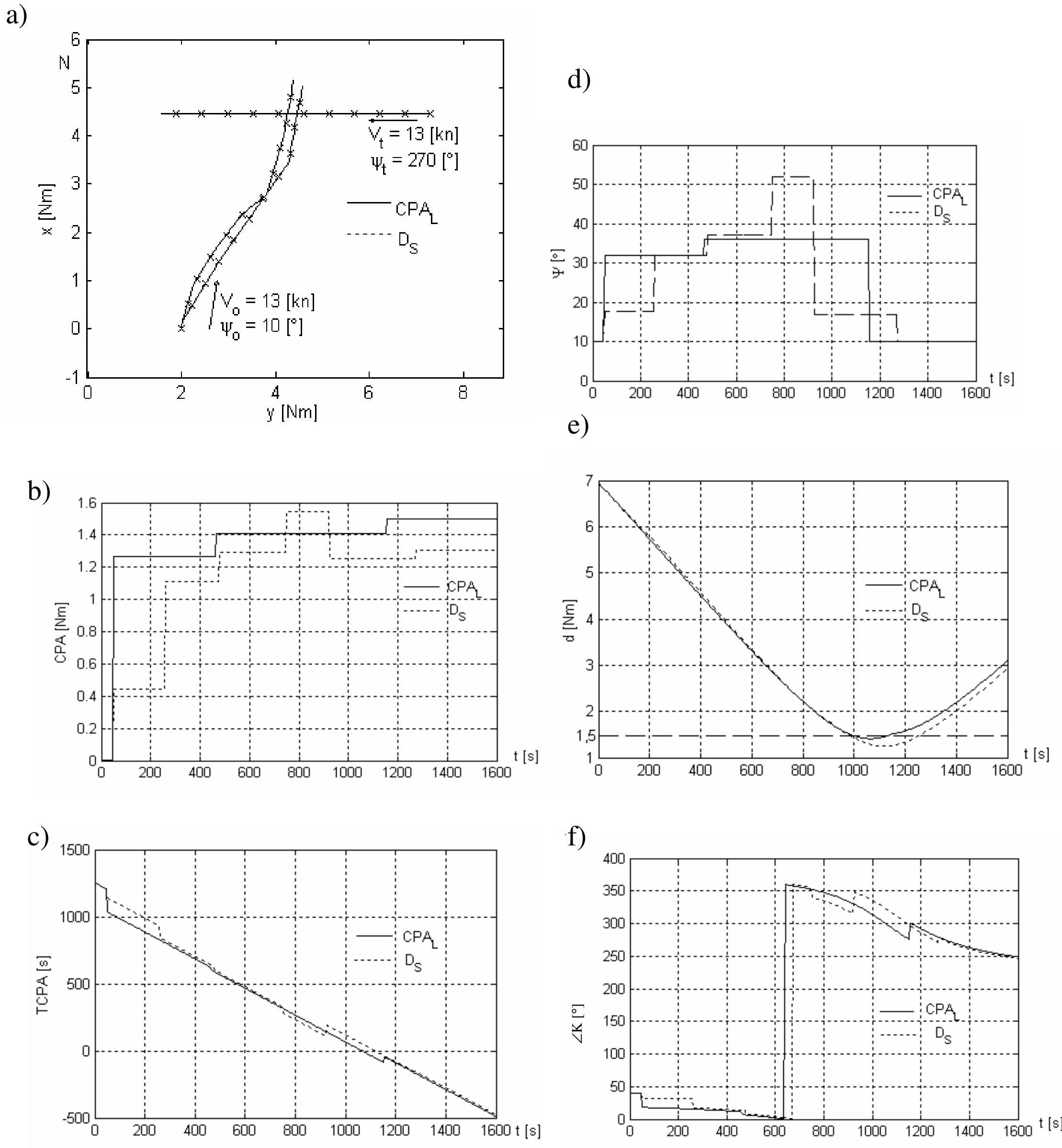

Figure 3. Ship control for the criteria of the closest point of approach CPA_L and ship domain D_S ; simulation time 1600 [s]: a) ships' movement trajectories - positions (x) at 150 [s] time intervals; b) CPA distances; c) time to closest point of approach; d) own ship's course; e) distances from the target ship; f) heading angles on the target ship

5.2 Ship Control Execution in a Fuzzy Environment

The results of the multi-stage control in a fuzzy environment are shown in Figure 4. Both maneuvers are characterized by the course changes causing a decrease in the distance between own ship and the other ship after the other ship finds itself on the heading angle on the (270°, 360°) interval.

The distances to the other ship while maneuvers were executed in the phase of passing are smaller than the distances for crisp (non-fuzzy) criteria of a navigational situation assessment.

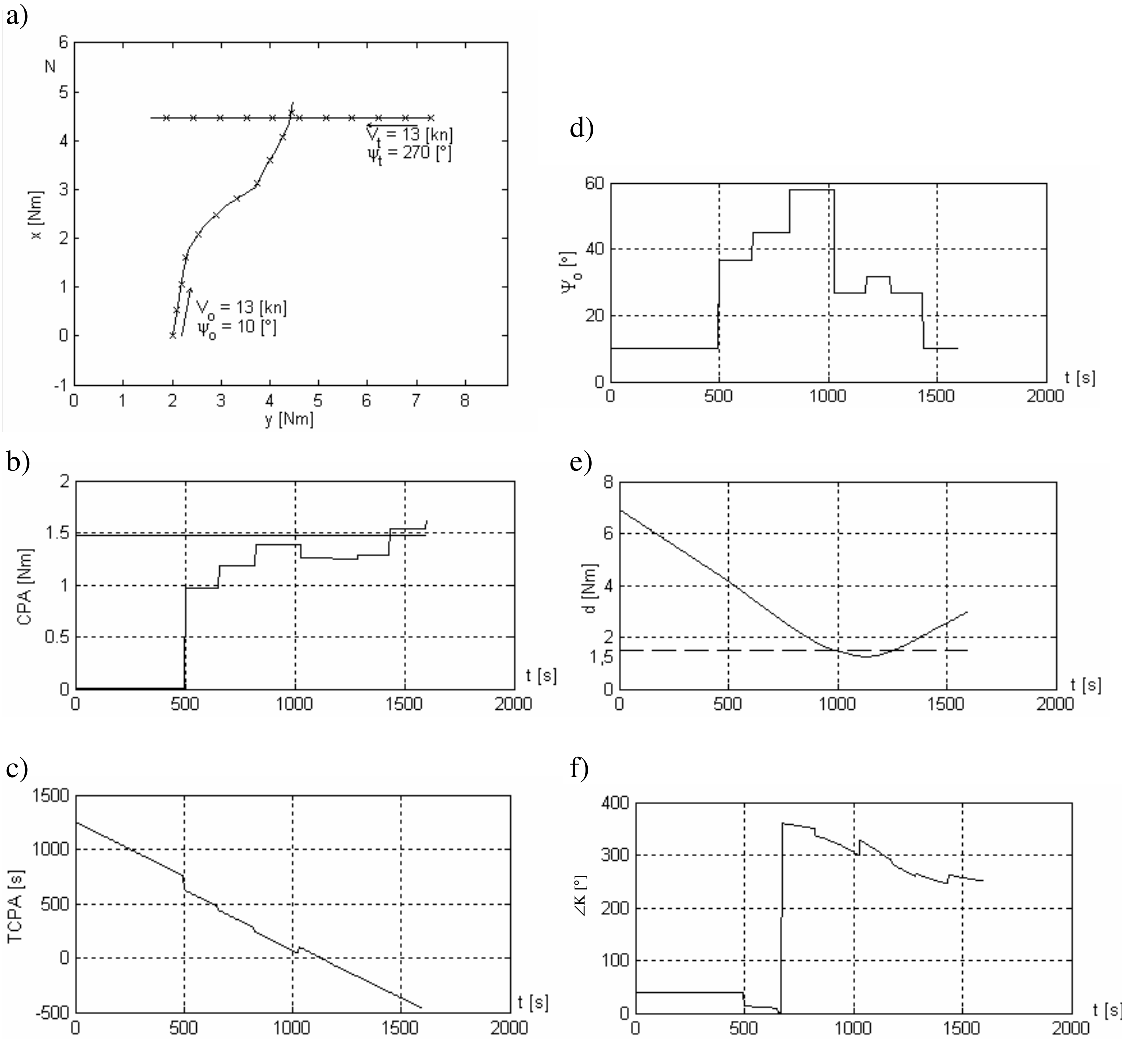

Figure 4. Multi-stage control in a fuzzy environment; simulation time 1600 [s]: a) ships' movement trajectories - positions (x) at 150 [s] time intervals; b) CPA distances; c) time to closest point of approach; d) own ships course; e) distances from the target ship; f) heading angles on the target ship

6. Summary

The ship trajectory defined by the decision support system should take into account regulations in force, assure safe maneuver and be rational. This means, *inter alia*, the application of criteria used and accepted by the human being. It is of importance for the system to be reliable, otherwise it will not be used in practice.

The presented methods and procedures for ship control make use of the knowledge of expert navigators. Simulation research was done for encounter situations in an open area. The results were analysed.

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