Ships’ domains as a collision risk at sea in the evolutionary trajectory planning

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Abstract

The goal of this paper is to discuss the problem of avoiding collisions at sea from the perspective of an evolutionary process and representation in this problem the risk of collision. In an evolutionary method (EP/N Evolutionary Planner Navigator System) of generating paths of the ship in partially-known environments is presented. Based on the E/PN planning concept, a modified version of the system has been developed which takes into account the specific character of the collision avoiding process. The main innovation of this modified version is the existence of different types of static and dynamic constraints, which reflect the real environment with moving strange ships (targets) and their dynamic characteristics. The evolutionary process which searches for a near-optimum trajectory in a collision situation takes into account a time parameter and the dynamic constraints, which treat to the risk of collision with meeting strange ships. The risk of the collision - shapes and dimensions of dynamic constrains depend on assumed safety conditions (i.e., the safe distance between the passing targets, their speed ratio, and bearing).

1 Introduction

The biggest collision threat, manifesting itself, among other effects, by numerous cases of ships taking the ground, is recorded in the areas of heavy navigation traffic (harbour entrances, coastal zones, narrow sea passages: canals and straits). These areas are also characterised by frequent restricted visibility. The way the ships move there is partially controlled by formally introduced traffic separation regions. However, the execution of other marine functions, such as ferry transportation, coastal fishing, tourist services, and other activities connected with the maintenance of the navigability of water lines, result in crossing the
traffic separation regions by certain craft. This creates additional collision threat. According to some sources (Dove et al. [2]), 85 per cent of collisions and singings result from human errors. Beside economical losses, accidents at sea may lead to irreversible losses in the human environment. In order to reduce this threat to the minimum, extensive works are widely carried out to develop a ship guidance system, which would guide the ship safely in complex navigational areas. The ship guidance systems were studied by Dove et al. [2]. In this work, the VTS system was used for estimating a ship trajectory along given water lines in the harbour. Burns [1] extended the problem by guiding a set of ships along a given route. Iijima et al. [7,8] and Witt et al. [23] worked out an autonomous ship guidance system. Hayashi et al. [6] proposed a system for avoiding collision in coastal zones in which the function of an electronic map was linked with the radar operation in order to evaluate the ship’s position and assess the navigational situation. Sudhendar et al. [20] formulated a list of requirements an intelligent guidance system was to comply with, and presented a review of the actual activities in this area.

The author of the present paper was engaged in problems of guiding ships in collision situations. In a series of articles (Śmierzchalski [13,14,15]) this problem was formulated as a multi-criterion optimisation task. Then, the problem was solved for static and moving constraints using the decision making system. The attempt to estimate the safe trajectory using genetic algorithms was presented by Furuhashi et al. [4]. Śmierzchalski [16,17] applied in his ship guidance system a new computer technique - evolutionary algorithms. Basing on the concept of the E/PN (Evolutionary/Planner Navigator) guidance system, presented by Michalewicz et al. [11,12], Lin et al. [10], Trojanowski et al. [22] and Xiao et al. [24], a modified version of that system was prepared for solving collision problems. The present paper is a continuation of author’s earlier works (Śmierzchalski [16,17,18,19]). Comparing to them, an additional parameter, the risk of the collision, was introduced to the system. The risk is modified for all met strangers targets.

2 Determination of the risk collision utilising CTPA (Collision Threat Parameters Area)

The method of specifying CTPA was created by A.Lenart [9]. In the conjugate system of co-ordinates of the position \((X,Y)\) and movement \((V_x, V_y)\) (see Fig. 1 (a)) A.Lenart drew a relation,

\[
Y = A_j X - B_j \tau 
\]

(1)

where: \(A_j = \frac{X_j Y_j \pm D_{j,CPA} \sqrt{D_j^2 - D_{j,CPA}^2}}{X_j^2 - D_{j,CPA}^2}\), \(B_j = A_j V_{Xj} - V_{Yj}\)

in which \(X_j\) and \(Y_j\) are the relative co-ordinates of j-th target and
\[ D_j^2 = X_j^2 + Y_j^2, \]

\( D_{JCPA} \) - the distance value of the closest contact,

\( V_{Xj}, V_{Yj} \) - X and Y components of the velocity vector of the j-th target,

\( \tau \) - conjugate time (e.g. 12 minutes).

Equation 1 describes the locus of points for which \( D_{JCPA} = \text{const} \) in the conjugate system of co-ordinates of position \((X, Y)\) and motion \((V_x, V_y)\). On the other hand the locus of points in the conjugate system of co-ordinates for which the time of reaching the distance of the closest contact is constant \((T_{JCPA} = \text{const})\) can be determined on the basis of the circle equation (2):

\[
\left[ X - \left( V_x + \frac{X_j}{2T_{JCPA}} \right) \tau \right]^2 + \left[ Y - \left( V_y + \frac{Y_j}{2T_{JCPA}} \right) \tau \right]^2 = \left( \frac{D_j \tau}{2T_{JCPA}} \right)^2 \tag{2}
\]

where the locus of points for the circle centre points lie on a straight line:

\[
Y = \frac{Y_j}{X_j} X - \left( \frac{Y_j}{X_j} V_{Xj} - V_{Yj} \right) \tau. \tag{3}
\]

It is assumed that an target \( B_j \) is dangerous, when at the moment of observation \( t \), assuming that \( D_{CPAj} = D_b \) and \( T_{CPAj} = T_b \) respectively we have:

\[ D_{JCPA} < D_b \quad \text{and} \quad T_{JCPA} < T_b \tag{4} \]

where: the values \( D_b \) of the safe distance and \( T_b \) - the time to reach that distance are set by the system operator (at say \( D_b = 1 \text{Nm}, T_b = 20 \text{ min} \)).

![Diagram](a) A CTPA area display, (b) The collision risk \( R \)

Geometrically the above condition is satisfied when the end of the vector of own
ship A positioned at \((V_x, V_y)\) in the conjugate system of co-ordinates of position and motion is found outside of the CTPA danger area. In the calculation algorithm the time of overtaking the manoeuvre of own ship and of targets was also respected. A practical realisation of visualisation of the total CTPA area determined for two targets with the proposal of the safe manoeuvre is pictured on Fig. 2. One of the drawbacks of the method presented here is that although the algorithm prescribes the manoeuvre leading out of the situation of collision created at a given time, it doesn't however assume the possibility of the appearance of new targets and does not state the moment of return of own ship to its planned course.

![Diagram of CTPA area](image)

**Fig. 2:** The practical realisation of CTPA area determined for two targets with the proposal of the safe manoeuvre

In order to evaluate the collision risk index (see Fig. 1 (b)) for one object the author suggests that the ranges of \(D_{j\, cpa}\) and \(T_{j\, cpa}\) values should be reduced to the real area of danger \(|D_{j\, cpa}| \in (0, D_b)\) and \(T_{j\, cpa} \in (0, nT_b)\) and \(n > 1\). To do this, the collision risk index was defined using the collision threat area, CTPA. In this area a number of non-linear functions are defined which give the maximum closure distance and time values with relation to the assumed quantities of \(D_b\) and \(T_b\). Such a form of the collision risk index takes into account the time-space relation, which is highly non-linear in the vicinity of the critical values of \(D_{j\, cpa}\) and \(T_{j\, cpa}\) for the situation of a collision danger at a given instant \(t\). The collision risk coefficient \(R\) (5) is depended on safe distance \(D_b\) and time to safe distance \(T_b\) defined by the following relationship (5), where: \(1 > R > 0, \ n > 1, \ a, b, c, d\) values of regulate the risk coefficient.

\[
\begin{align*}
\min R &= \begin{cases} 
\alpha \left[e^{\left(\frac{D_{j\, cpa}}{D_b}\right)^2} - 0.1\right]\frac{T_{j\, cpa} + c}{T_b} - d & \text{for } D_{j\, cpa} < D_b, \ T_{j\, cpa} < nT_b \\
0 & \text{for } D_{j\, cpa} \geq D_b, \ T_{j\, cpa} \geq nT_b
\end{cases}
\end{align*}
\]
3 Domain estimation for approaching moving targets

A moving target representing a collision threat is configured as an area of danger, moving with the speed and at the direction (course) identified by the ARPA system. The most significant factors affecting the scale of the ship domain are the following: (1) psychological, human factors, such as: naval experience of the navigator, along with his intuition and knowledge on the navigation area, (2) physical factors, characteristic of the type of the ship, referring to its dimensions, relative speed of other approached ships, (3) physical factors, common for all ships in the area of concern, such as traffic level, hydro-meteorological conditions, etc. Goodwin E.M. [5] presented the method for estimating the area of danger on the basis of statistical data analysis. Following the maritime law regulations, the area of the object occurrence was divided into three sectors defined by the actual relative bearing to this object. Sector 1 is on the starboard side within the bearing limits of $0^\circ < \theta \leq 112.5^\circ$, sector 2 is on the port side within $247^\circ \leq \theta < 360^\circ$ and the stern sector 3 is within $122.5^\circ < \theta < 247.5^\circ$. The dimensions of the domains were estimated on the basis of statistical data. A sample ship domain is shown in Fig. 3a. A modified domain formula, which made its modelling easier, was proposed by Davis P.V. et al [3] Fig. 3b. The author proposed to describe the area of danger around the object using a hexagon, whose dimensions are to be chosen experimentally.

![Fig. 3: Domains of objects according to a) Goodwin, b) Davis c) present work](image)

Its manoeuvres are chosen in such a way that the restricted areas surrounding the targets and fixed obstacles are not intruded on at any time. In order to make the own ship’s manoeuvres match the regulations of IML, the following assumptions were to be made when estimating the domain: (1) the area was of different structure for good and for limited visibility, (2) for good visibility, the hexagon dimensions on the port side of the target should be the largest, which in the case of course crossing will make the manoeuvre of the own ship giving way be done at a sufficient distance from the target, (3) this distance should be equal to or greater than the distance at which the target is allowed to start manoeuvres mentioned in Rule 17 a)ii). It was assumed (Fig. 4) in that the excessive approach in Sectors H,I,J,A occurs at a distance smaller than $D_b$, assumed here as equal to 2 nautical miles. In Sector B this distance is equal to $0.67 D_b$, and in the remaining sectors it is assumed the same as in Sector B. Points M, N were...
selected in such a way as to be on line with the course 090°-270°, which corresponds to the ship’s beam. By decreasing the distance to the excessive approach in the sectors, a hexagon-shaped domain was obtained which is dependent on actual value of $D_h$, assumed by the navigator. The disadvantage of this method is that $D_h$ assumed is valid for one ship only. In the case of restricted visibility the problem of interpretation of Rule 17 is no longer valid. Rule 19 does not recognise ships with the right of way. Types and distances of the preventing action depend only on whether the target is behind the stern, in front of the bow, or on the ship beam. This regulation also recognises a conception of an excessive approach to be avoided. That means that in restricted visibility the domain should be determined using the excessive approach distance curves. In front of the bow this distance should equal at least 2 to 3 nautical miles at open sea, while in Cockroft diagram, manoeuvres at a distance larger than 4 nautical miles are recommended. Here, the crucial factor is the relative speed of the two ships approaching each other. When one ship overtakes the other, or passes it from astern, the excessive approach distance can be reduced to 2 Mm, and even less if relative speeds of the objects are not large.

Fig. 4: (a) Hexagon-shaped ship domain. (b) Hexagon around moving target

4 Concept of creating hexagonal domains as the risk of collision

The assumed concept of hexagon-shaped domains around moving targets makes it possible to take into account those objects as dynamic obstacles in the evolutionary algorithm 9EP/N++ used for estimating optimum safe trajectories. The process of creating of a hexagon-shaped area of danger – risk of collision around a given target is shown in Fig. 4(b).

The lengths of the ship domain, in the bow and stern directions - parameters determining the dimension of the domain in the horizontal plane, in nautical
miles (or meters), calculated from the centre of the system in the bow direction (5) and (2), (4) as well as in the stern direction (6) to its limiting value. The appearance of a navigational constraint in the vicinity of the domain contour, or at a distance ahead on the planned passing trajectory (which depends on the navigator’s experience) means the appearance of a navigational risk and its increase resulting from the decreasing distance to the detected constraint. For the ship on its course, the longitudinal dimension of the domain (its dynamical length) \(L_D\) can be evaluated using the formula [21]:
\[
L_D = d_3 = L \sqrt{V^2 + 30 V + U}
\] (6)
where: 
- \(L\) - ship length (here, the length \(L\) of the own ship is used instead of, an unknown, length of the ship detected by the ARPA system),
- \(V\) - ship speed, \(V_O > V_{REL} \Rightarrow V = V_O, V_O < V_{REL} \Rightarrow V = V_{REL}\)
- \(V_O\) - own ship speed, \(V_{REL}\) - relative speed of strange ship,
- \(U\) - error in estimating ship location, determined with 95% probability, \(U = 2M = 0.1 \text{Mm}, M\) – standard quadratic error of the ship location.

The level of navigational risk related to the length of the ship domain, which can be interpreted as the probability of collision with a navigational constraint in the horizontal plane, is reflected, to some extent, by the widely used in ARPA systems concept of \(T_{CPA}\) (Time of Closest Point of Approach), i.e. the time left to the instant when the closest point of approach, \(D_{CPA}\) is reached. With decreasing ratio between the distance from the detected navigational constraint and the ship domain length, the time \(T_{CPA}\) left for reaching \(D_{CPA}\) (\(T_{CPA}\)), decreases as well, which means the increasing risk of the navigational collision.

\[
d_3 = T_{CPA0} \sqrt{V + U}
\] (7)
\[
d_4 = T_{CPA0} \sqrt{V + U}
\] (8)
where: \(T_{CPA0}\) - assumed value of \(T_{CPA}\)

After the stern, on the other hand, it is sufficient for the distance parameter equal
\[
d_6 = D_b E \quad \text{or} \quad d_6 = D_b/2
\] (9)
but not less than 0,5 Mm, where: \(E\) – relative speed to own speed ratio: \(V_{REL}/V_O\)

The widths of the ship domain, on the starboard or port sides - parameters determining the dimension of the domain in the horizontal plane, in nautical miles (or meters), calculated from the centre of the system in the starboard (4) or port side (5) directions of the ship to its limiting value. The equivalent of the width of the domain is the commonly used concept of the minimum distance \(D_{min}\) (\(D_{CPA}\)), which determines (in ARPA systems, for instance) the minimum area around the ship, which is to be kept clear by the navigator when passing another ship or a fixed navigational constraint. For the ship on its course, the lateral dimension of the domain (its dynamical width) \(B_D\) can be evaluated using the formula [21]:
\[
B_D = d_3 = B \sqrt{V^2 + 44} + U \quad \text{but} \quad d_3 > D_{CPA0}
\] (10)
where: 
- \(B\) – ship width (here, the width \(B\) of the own ship is used instead of, an unknown, width of the ship detected by the ARPA system), \(D_{CPA0}\) - assumed value of \(D_{CPA}\), \(D_{b}\)

The above width of the domain is valid for the starboard side. On the port side,
however, like after the stern:

\[ d_i = D_{CPA0} E \quad \text{or} \quad d_i = D_{CPA0}/2, \quad \text{but no less than } 0.5 \text{ Nm} \quad (11) \]

where: \( E \) - relative speed to own ship speed ratio: \( V_{REL}/V_O \).

### 5 Exemplary planning of ship trajectory

The system of evolutionary planning of the ship trajectory was tested for the numerous cases of passing fixed navigational constraints and moving targets. The analysis of cases displays the need for the introduction of an additional parameter to the evolutionary trajectory planning algorithm, namely the change of the own ship’s speed along particular trajectory sections and ships’ domains (see: Fig. 5). In practice, the speed was modified using an additional genetic operator: the speed mutation. A set of permissible speed values was defined as \( V = \{3.6; 8.6; 13.6 \text{ knots}\} \) from which the mutation operator could take a speed at the trajectory section of concern. Additionally, the total time of trajectory passing was added to the function of the trajectory fitness, which took into consideration changes in the own ship’s speed. After this modernisation of the evolutionary process of the trajectory search, a trajectory will be looked for which, besides meeting the formerly set safety and economy conditions, will represent the shortest time needed for covering the studied distance. For this version of the algorithm, the example represents the moving targets sailing with opposite courses on the right and left sides of the own ship - a ferry, constraints having the form of islands. Here, the population consisted of 40 individuals (passage trajectories), and the changes of trajectories in the population stopped being recorded after 1000 generations. The estimated trajectories secure the passage of the ferry behind the stern of the targets on the left side. The ship’s speed changed from one trajectory section to another. Initially, the ship reduced its speed to pass targets on the left side, then, having sailed between the islands it increased the speed as it did not produce unacceptable nearing to target on the right side.

### 6 Conclusions

The evolutionary system of ship trajectory planning makes it possible to steer the ship in a well known environment both with static, and dynamic navigation constraints, as well as to make adaptation corrections of the ship trajectory in order to follow unforeseeable changes in the situation at sea. The evolutionary method of determining the safe and optimum trajectory in the environment is a new approach to the problem of avoiding collisions at sea. A number of preliminary tests have made it possible to formulate the following conclusions:

- evolutionary algorithms can be effectively used for solving the problem of planning ship trajectory in areas of extensive traffic, like harbour entrances, coastal regions,
Fig. 5: Trajectory evolution for the case of approaching moving targets in the presence of static navigation constraints (population 40 trajectories).

- introduction of the own ship’s speed as a changing parameter makes it possible to solve the problem in a wider range. For particular trajectory sections, the actual speed is evaluated with which the ship covers this section in order to pass safely and economically all navigational constraints, both fixed and moving.

References


Section Two:

Estimation of risks