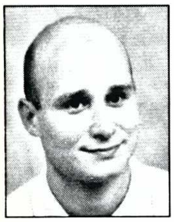

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Decision making criteria in autonomous simulation model of ship movement in limited sea areas

SUMMARY

Autonomous simulation of ship movement, i.e. simulation without human factor applied directly to steering , but rather indirectly with the use of expert database or artificial intelligence methods, can be very effective at early stages of the fairway boundary designing and manoeuvre area determining. A verified autonomous model working in fast time is much less time consuming and no expert navigator requiring in comparison to a classic simulation model. This paper presents calculation methods of a distance to fairway boundary and of domain designation used in such model of automatic ship movement. Final algorithm of domain designation is optimized according to time duration and calculation accuracy. The calculated parameters serve as criteria for the next manoeuvre decision. An exemplary algorithm of the autonomous simulation model of ship movement in fast (accelerated) time, based on these asumptions is presented.

INTRODUCTION

The development of numerical calculation techniques comes together with new simulation methods of fairway measuring and designing. The number of information directly available to navigator from electronic navigation aids becomes higher and higher as well. Electronic Chart and Display Systems (ECDIS) are commonly used with modern ships. Numerical storage of radar and classical charts in the form of a discrete matrix of points which can be readily transformed, opens new possibilities for increasing the navigation safety. The numerical vector chart becomes a database for automatic manoeuvres in limited sea areas, performed either directly with the use of a computer, or indirectly by applying an expert system.

The bank lines, depth contours, navigation signs, obstructions and fairway lines used in a simulation model of ship movement usually consist of several closed and open geometric figures made of straight-line segments. Those objects are treated as the lines restricting the manoeuvre area available to a ship. Similar rules can be applied to an electronic vector chart. The analysis of domain ranges and dimensions around vessel relative to such restricting line will provide criterion for making decision of a given manoeuvre in autonomous simulation of ship movement in limited sea areas [6].

The panoramic presentation was chosen to keep clarity of the pictures in this paper. Geometric qualities of straight lines, line segments, vectors, circles and ellipses were analyzed to calculate the distance between a chosen point of ship waterline contour and the line restricting the manoeuvre area and to control the ship domain. In the 1st chapter of this paper the way is shown of figuring the on-course distance from the foremost ship-waterline point to the restricting line. In the 2nd chapter the way is presented of determining the minimum range between a chosen point of ship waterline and the restricting line. In the 3rd chapter the way of calculating and controlling dimensions and shape of an elliptical domain is described. Finally an exemplary algorithm is presented of the autonomous simulation model of ship movement as well as results of autonomous steering and that performed by human operators are compared.

CALCULATION OF THE ON-COURSE DISTANCE FROM THE FOREMOST POINT OF SHIP WATERLINE CONTOUR TO THE LINE RESTRICTING THE MANOEUVRE AREA

Because the restricting lines are implemented in the simulation model as a matrix of points $P_i(x_i, y_i)$ the first step of computing the distance to such a line is to get the number of *i-th* segment lying at the crossing of ship's true course (*i-th* segment begins at the point P_i and ends at the point P_{i+1}). To do this the co-ordinates of the point $P_{Pi}(x_{Pi}, y_{Pi})$ of the intersection of the course line with a line passing through *i-th* segment of the restricting line, are found by solving the equation system of straight lines :

$$\begin{cases} (y_{Pi} - y_i)(x_{i+1} - x_i) = (y_{i+1} - y_i)(x_{Pi} - x_i) \\ (y_{Pi} - y_D)(x_S - x_D) = (y_S - y_D)(x_{Pi} - x_D) \end{cases} \tag{1}$$

where from :

$$x_{Pi} = \frac{x_D(y_S - y_D)(x_{i+1} - x_i)}{(y_S - y_D)(x_{i+1} - x_i) - (x_S - x_D)(y_{i+1} - y_i)} + \\ - \frac{(x_S - x_D)[x_i(y_{i+1} - y_i) + (x_{i+1} - x_i)(y_D - y_i)]}{(y_S - y_D)(x_{i+1} - x_i) - (x_S - x_D)(y_{i+1} - y_i)} \tag{2a}$$

$$y_{Pi} = \frac{(y_S - y_D)[y_i(x_{i+1} - x_i) + (y_{i+1} - y_i)(x_D - x_i)]}{(y_S - y_D)(x_{i+1} - x_i) - (x_S - x_D)(y_{i+1} - y_i)} + \\ - \frac{y_D(x_S - x_D)(y_{i+1} - y_i)}{(y_S - y_D)(x_{i+1} - x_i) - (x_S - x_D)(y_{i+1} - y_i)} \tag{2b}$$

where :

(x_D, y_D) - co-ordinates of the foremost point of ship waterline contour

(x_S, y_S) - recorded co-ordinates of the centre of ship waterline.

In the next step of the algorithm the equality of signs of the co-ordinates of the vectors $\overrightarrow{P_S P_D}$ and $\overrightarrow{P_D P_{Pi}}$ is tested to eliminate the indication ambiguity of the point P_{Pi} (if ahead of the bow or behind the stern of the ship) :

$$\begin{aligned} x_{SD} &= x_D - x_S & y_{SD} &= y_D - y_S \\ x_{DPi} &= x_{Pi} - x_D & y_{DPi} &= y_{Pi} - y_D \\ x_{SD} \cdot x_{DPi} &> 0 & y_{SD} \cdot y_{DPi} &> 0 \end{aligned} \tag{3}$$

Evaluation of the condition (4) provides the answer to the question if the point P_{Pi} is really included in *i-th* segment and not only in a line passing through it :

$$[(x_{Pi} < x_i) \wedge (x_{Pi} < x_{i+1})] \vee [(x_{Pi} > x_i) \wedge (x_{Pi} > x_{i+1})] \vee \\ \vee [(y_{Pi} < y_i) \wedge (y_{Pi} < y_{i+1})] \vee [(y_{Pi} > y_i) \wedge (y_{Pi} > y_{i+1})] \tag{4}$$

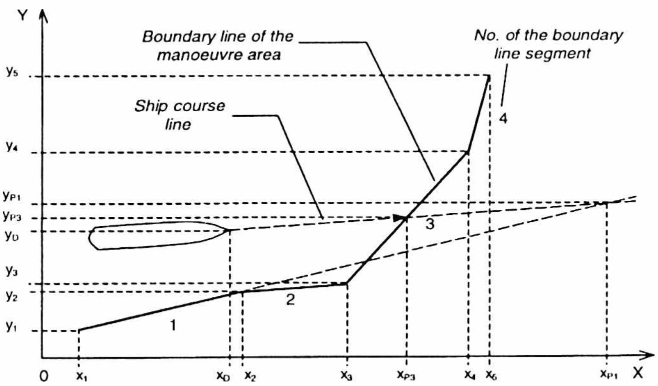

Fig.1. Graphical presentation of the condition (4) in the Cartesian co-ordinate system XY

In the figure the exemplary ship waterline position relative to the restricting line is presented. The point (x_{P1}, y_{P1}) meets the condition (4) because it is not included in segment 1. In such case the on-course distance to segment 3, i.e. to the point (x_{P3}, y_{P3}), will be calculated.

When the condition (4) is not satisfied the right *i-th* segment of the restricting line and the right P_{Pi} point is found (Fig.1). Otherwise, when the condition (4) is fulfilled calculations for *(i+1)-th* segment are performed.

The distance to an ahead obstacle or that between the foremost ship-waterline point $P_D(x_D, y_D)$ and the point $P_{Pi}(x_{Pi}, y_{Pi})$ of the intersection point of the course line with the segment of restricting line, is computed when the right segment of the restricting line is found :

$$d_{ah} = P_D P_{Pi} = \sqrt{(x_{Pi} - x_D)^2 + (y_{Pi} - y_D)^2} \tag{5}$$

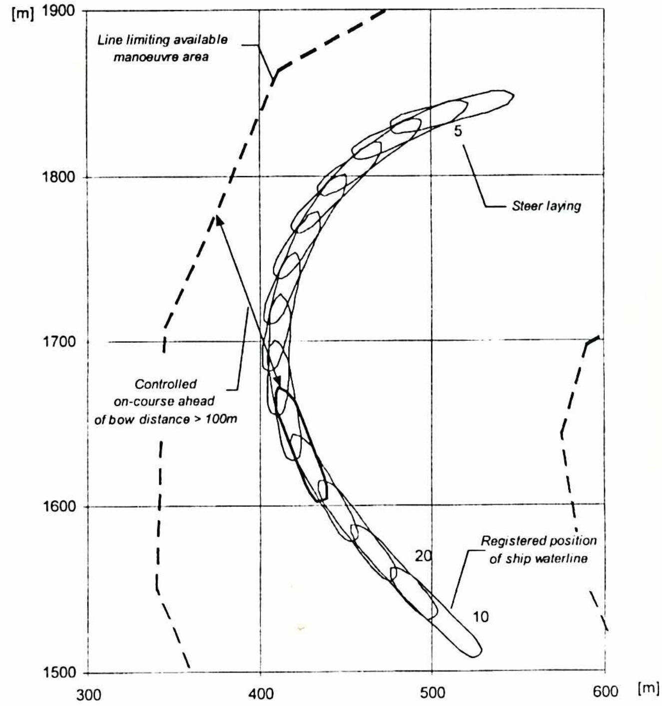

Fig.2. The trajectory of LPG tanker (of L/B/d = 69m/12m/4.2m) recorded at every 10s instant while controlling the ahead-of-bow distance

CALCULATION OF THE MINIMUM DISTANCE FROM A CHOSEN SHIP-WATERLINE POINT TO THE RESTRICTING LINE

To determine the minimum distance from a chosen ship-waterline point to the restricting line, a distance to the orthogonal projection of this point onto the line containing *i-th* segment of the restricting line is calculated. In the case of the foremost waterline point $P_D(x_D, y_D)$ this distance is as follows :

$$d_{Ri} = P_D P_{PPi} \tag{6}$$

The co-ordinates of the orthogonally projected point $P_{PPi}(x_{PPi}, y_{PPi})$ are found by solving the following system of equations :

$$\begin{cases} (y_{PPi} - y_i)(x_{i+1} - x_i) = (y_{i+1} - y_i)(x_{PPi} - x_i) \\ (y_{i+1} - y_i)(y_{PPi} - y_D) = -(x_{i+1} - x_i)(x_{PPi} - x_D) \end{cases} \tag{7}$$

where from :

$$\begin{aligned} x_{PPi} &= \frac{(y_{i+1} - y_i)(x_{i+1} - x_i)(y_D - y_i)}{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} + \\ &+ \frac{x_D(x_{i+1} - x_i)^2 + x_i(y_{i+1} - y_i)^2}{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \\ y_{PPi} &= \frac{(x_{i+1} - x_i)(y_{i+1} - y_i)(x_D - x_i)}{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} + \\ &+ \frac{y_D(y_{i+1} - y_i)^2 + y_i(x_{i+1} - x_i)^2}{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \end{aligned} \tag{8}$$

Then the condition analogous to (4), of the projected point containment in *i-th* segment, is checked and the distance d_{Ri} to the determined segment is calculated according to (5).

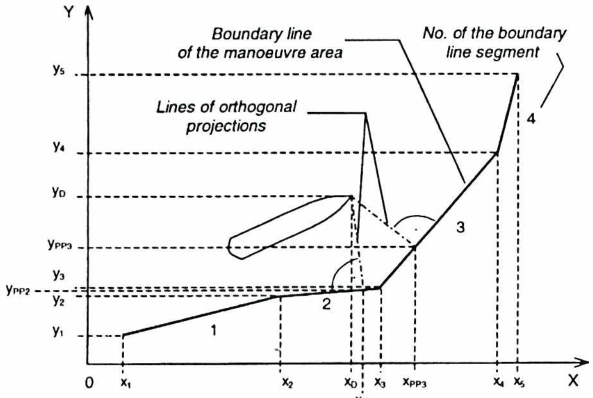

Fig.3. Calculation of the minimum distance from the foremost ship-waterline point to the restricting line

In the figure the exemplary ship waterline position relative to the restricting line is presented. Both points: of (x_{PP2}, y_{PP2}) and (x_{PP3}, y_{PP3}) co-ordinates do not meet the condition (4) so both distances (to segments 2 and 3) will be calculated.

As it is shown in Fig.3 the counter i of the segments must be increased and the distances to the next consecutive segments in which the projected point is included must be checked according to the condition (4). The smallest of the distances d_{Ri} will be the minimum distance d_R to the restricting line.

DESIGNATION OF DOMAIN SHAPE AND DIMENSIONS

The domain concept was introduced to navigation and sea traffic engineering with the intention to formalize the description of the collision risk phenomena as an area around vessel the navigator tries to keep from being crossed by other objects [1]. Determination of the minimum distance of a chosen ship-waterline point to the line restricting the manoeuvre area, d_R, and next its comparison with the assumed safe distance d_s is equivalent to designation of a circular domain. In the case of more complex domains the algorithms directly based on curve equations would be too time consuming and susceptible to rounding errors. For instance in the „direct" method of checking if two line segments cross each other the use of a division operation is needed to find the exact point of intersection (see equation 2). If the segments are almost parallel then this method is very sensitive to the accuracy of the division operation implemented in the computer. The below described method of domain designation is much more precise as it avoids using the division operation and trigonometric functions in the executive loop of the simulation program.

A domain of an arbitrary shape can be designed by digitizing the continuous line to a number of the most significant points (e.g. to 12 points as shown in Fig.4) in a similar way as for the ship waterline in the simulation model.

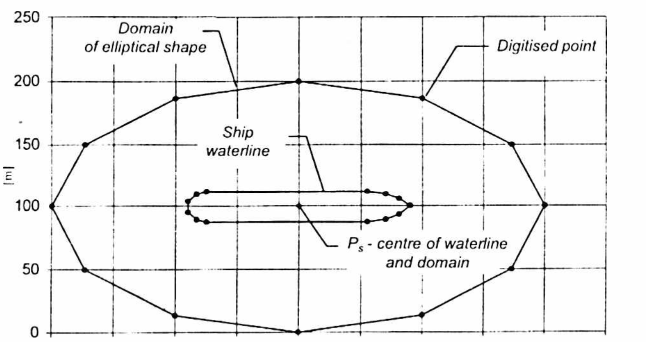

Fig.4. The elliptical domain of the axes : a = 200 m, b = 100 m, set up by digitizing 12 points and drawing line segments

The points shown in the figure meet the parametric equations :

$$x = a\cos\phi + 200 \qquad y = b\sin\phi + 100$$

The ship waterline set up by connecting 13 points lies inside the domain.

Next, simultaneously with the calculations of new waterline positions, the new positions of the domain, i.e. the co-ordinates of the points determining the domain, will be calculated in the executive loop of the program. Now all that is needed to determine the collision risk is to check during the simulation run if any of the domain segments intersects a segment of the restricting line.

The process of checking if two line segments $\overline{P_iP_{i+1}}$ and $\overline{P_jP_{j+1}}$ cross each other consists of two steps. The first is quick elimination. Two line segments cannot cross each other if their rectangular constraints do not cross each other. The rectangular constraint of a geometric figure is the smallest rectangle with sides parallel to the co-ordinate system axes, which contains that figure. The rectangular constraint of the segment $\overline{P_iP_{i+1}}$ is the rectangle $(\hat{P}_i, \hat{P}_{i+1})$ defined by the left lower corner $\hat{P}_i = (\hat{x}_i, \hat{y}_i)$ and right upper corner $\hat{P}_{i+1} = (\hat{x}_{i+1}, \hat{y}_{i+1})$, where :

$$\hat{x}_i = \min(x_i, x_{i+1}) \qquad \hat{y}_i = \min(y_i, y_{i+1})$$

$$\hat{x}_{i+1} = \max(x_i, x_{i+1}) \qquad \hat{y}_{i+1} = \max(y_i, y_{i+1})$$

Two rectangles represented by their left lower and right upper corners $(\hat{P}_i, \hat{P}_{i+1})$ and $(\hat{P}_j, \hat{P}_{j+1})$, cross each other if and only if the conjunction (9) is true :

$$\left(\hat{x}_{i+1} \ge \hat{x}_j\right) \wedge \left(\hat{x}_{j+1} \ge \hat{x}_i\right) \wedge \left(\hat{y}_{i+1} \ge \hat{y}_j\right) \wedge \left(\hat{y}_{j+1} \ge \hat{y}_i\right) \qquad (9)$$

The second step of checking if two segments cross each other is to examine if every of these segments crosses a line containing the other segment. The signs of vector products

$$\overrightarrow{P_iP_j} \times \overrightarrow{P_iP_{i+1}}, \ \overrightarrow{P_iP_{j+1}} \times \overrightarrow{P_iP_{i+1}}, \ \overrightarrow{P_jP_i} \times \overrightarrow{P_jP_{j+1}} \text{ and } \overrightarrow{P_jP_{i+1}} \times \overrightarrow{P_jP_{j+1}}$$

are tested to do this :

$$\begin{aligned} \overrightarrow{P_iP_j} \times \overrightarrow{P_iP_{i+1}} &= (P_j - P_i) \times (P_{i+1} - P_i) = \\ &= (x_j - x_i)(y_{i+1} - y_i) - (x_{i+1} - x_i)(y_j - y_i) \end{aligned} \qquad (10\ a)$$

$$\begin{aligned} \overrightarrow{P_iP_{j+1}} \times \overrightarrow{P_iP_{i+1}} &= (P_{j+1} - P_i) \times (P_{i+1} - P_i) = \\ &= (x_{j+1} - x_i)(y_{i+1} - y_i) - (x_{i+1} - x_i)(y_{j+1} - y_i) \end{aligned} \qquad (10\ b)$$

$$\begin{aligned} \overrightarrow{P_jP_i} \times \overrightarrow{P_jP_{j+1}} &= (P_i - P_j) \times (P_{j+1} - P_j) = \\ &= (x_i - x_j)(y_{j+1} - y_j) - (x_{j+1} - x_j)(y_i - y_j) \end{aligned} \qquad (10\ c)$$

$$\begin{aligned} \overrightarrow{P_jP_{i+1}} \times \overrightarrow{P_jP_{j+1}} &= (P_{i+1} - P_j) \times (P_{j+1} - P_j) = \\ &= (x_{i+1} - x_j)(y_{j+1} - y_j) - (x_{j+1} - x_j)(y_{i+1} - y_j) \end{aligned} \qquad (10\ d)$$

The idea is to check if the vectors $\overrightarrow{P_iP_j}$ and $\overrightarrow{P_iP_{j+1}}$ have different orientations in relation to $\overrightarrow{P_iP_{i+1}}$, and vectors $\overrightarrow{P_jP_i}$ and $\overrightarrow{P_jP_{i+1}}$ have different orientations in relation to $\overrightarrow{P_jP_{j+1}}$. If it is true then the segments $\overline{P_iP_{i+1}}$ and $\overline{P_jP_{j+1}}$ cross each other. In this case signs of the products (10 a) and (10 b) are different and simultaneously signs of the products (10 c) and (10 d) are different.

ALGORITHM OF AN AUTONOMOUS SIMULATION MODEL OF SHIP MOVEMENT

Several assumptions were made at the current stage of autonomous simulation model development. The analyzed water region was additionally limited by port and starboard restricting lines with safe manoeuvring area between them (they can be seen as boundary isobaths for a given ship draught). The steering was performed by using the rudder only for a ship at the constant dead slow-ahead order to the engine. The domain of equal distance from all points of the ship waterline (elliptical one) was assumed as the decision criterion. This criterion is checked at every discrete time interval (t_c) during manoeuvre prediction lasting another discrete time ahead (t_k) in fast time. The ship trajectory which meets the criterion (no boundary line inside domain) is recorded. An exemplary algorithm of the autonomous simulation model based on a semi--empirical mathematical model of ship movement is demonstrated in Fig.5. The screen image displayed by the computer during a simulation experiment is presented in Fig.6.

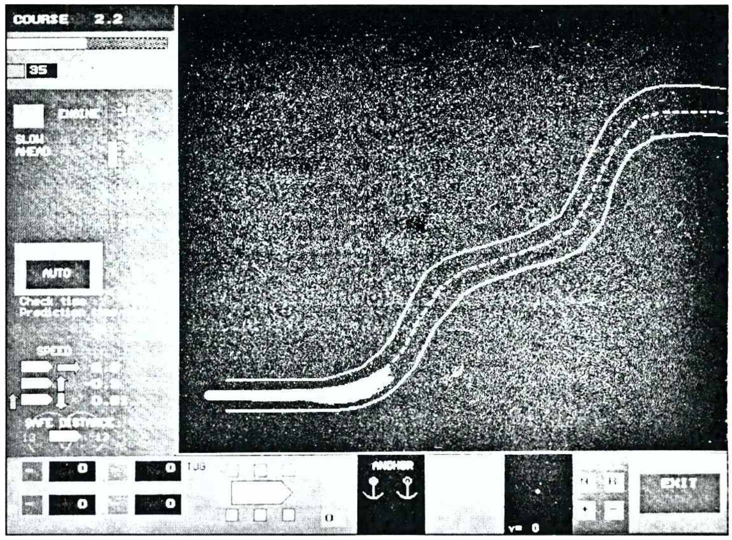

Fig.6. Exemplary screen image displayed by computer during autonomous simulation experiment

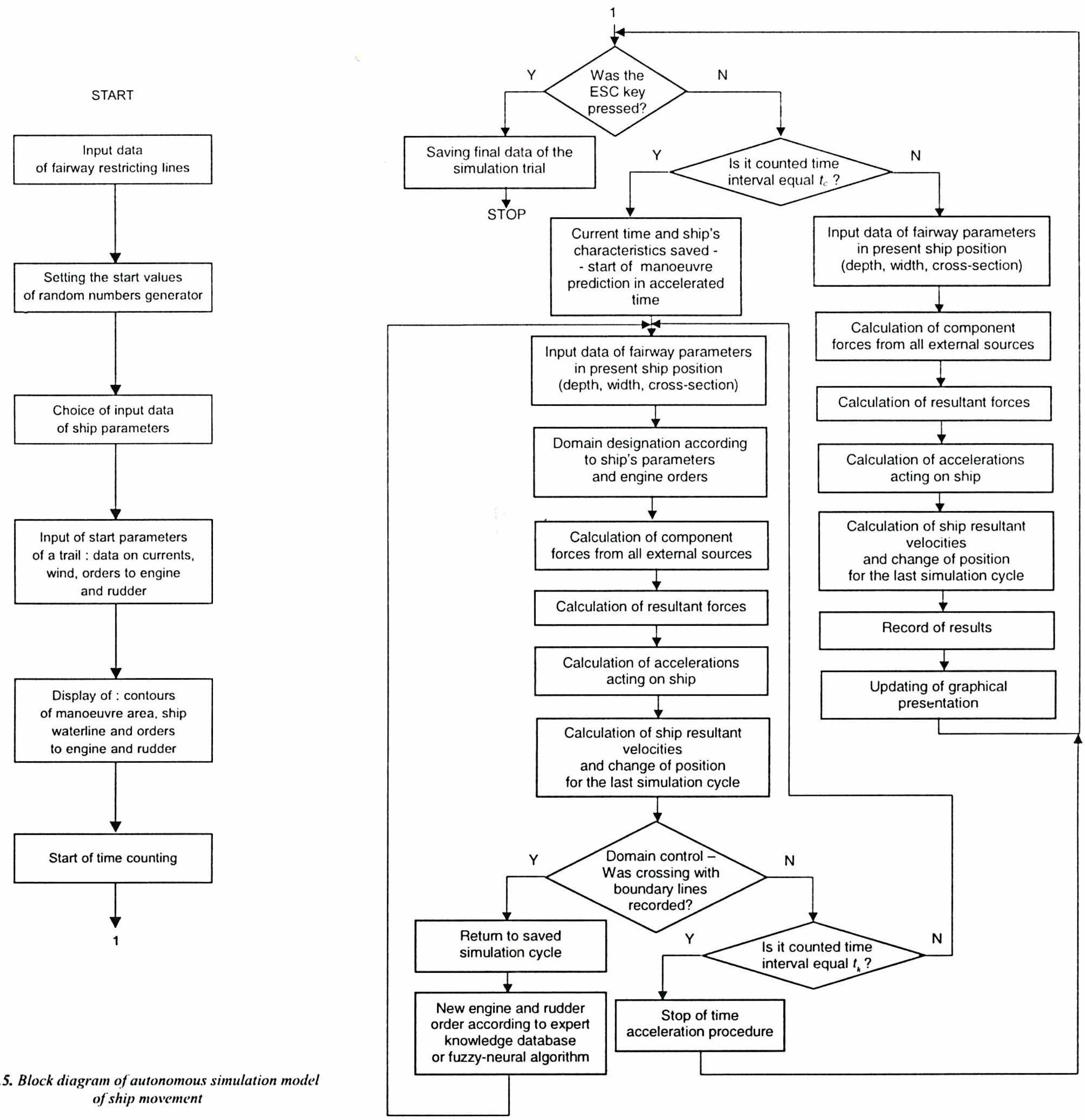

Fig.5. Block diagram of autonomous simulation model of ship movement

The trial manoeuvring area was chosen as a part of a fairway consisting of straight and curved segments (Fig.7). The widths of the fairway were determined by means of the analytical methods described in [4] for a ship of the following parameters :

- length overall - 75m
- breadth - 12m
- operating draught - 4.2m
- no trim or heel
- ship fitted with a controllable pitch propeller.

Fig. 8, 9, 10, 11 present results obtained from simulation trials in fast and real time (autonomously executed and by operator).

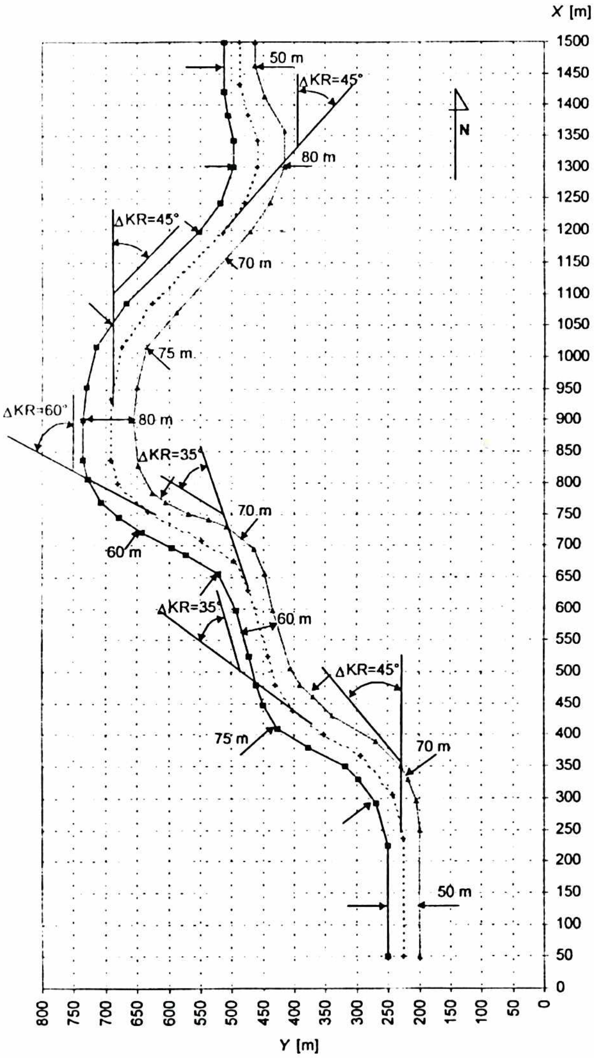

Fig.7. The simulation trial area of the dimensions determined by analytical methods

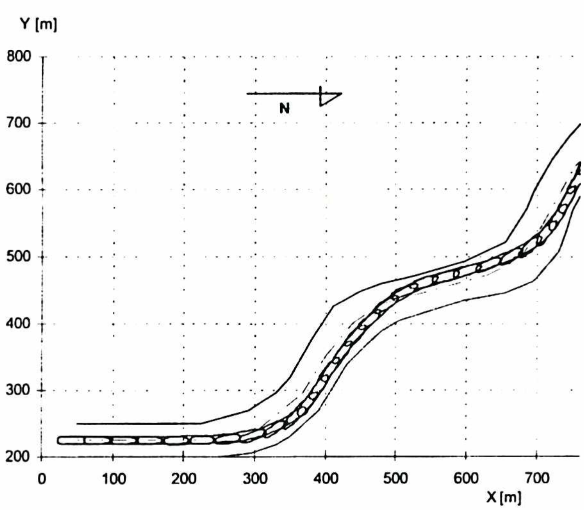

Fig.8. A fragment of the recorded trajectory of the ship steered automatically in fast time : t_c=10s, t_k=20s+40s - two consecutive manoeuvres predicted, domain of ship waterline shape

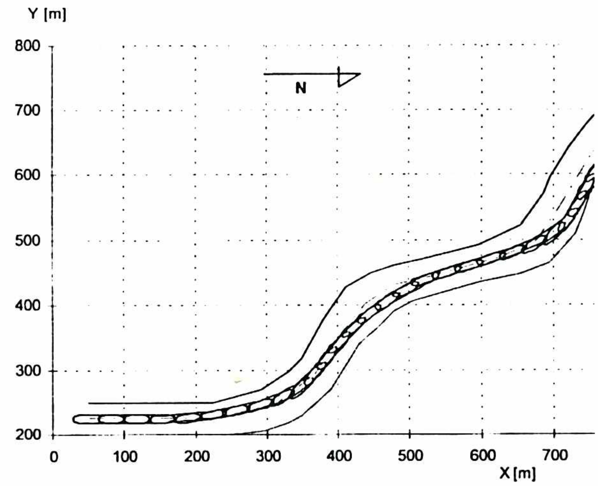

Fig.9. A fragment of the recorded trajectory (10s interval) of the vessel steered manually in real time

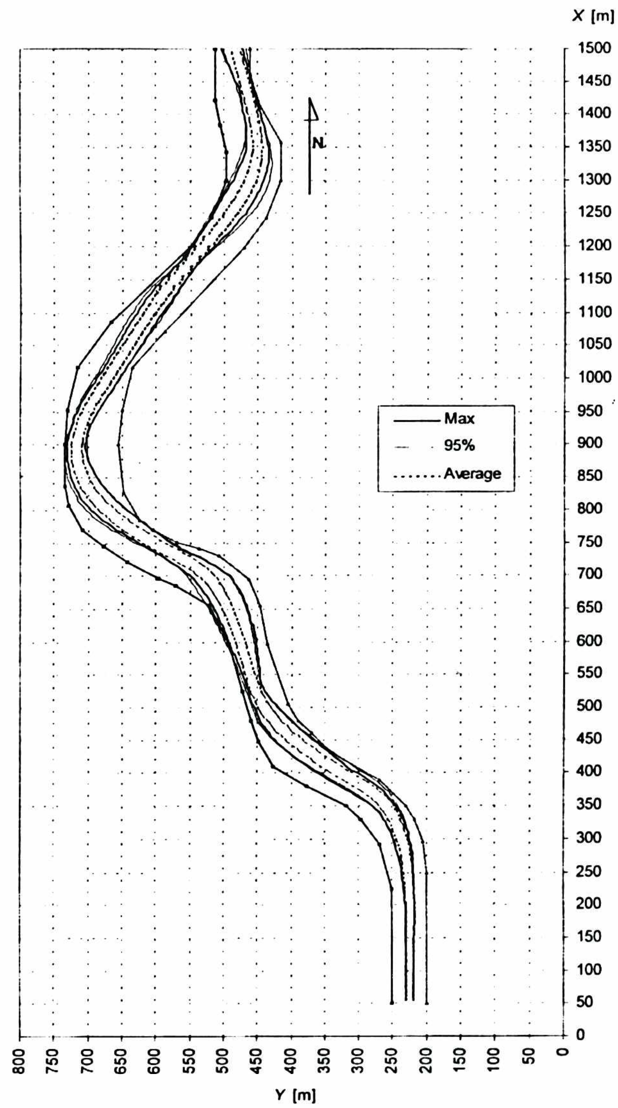

Fig.10. The statistically determined movement area of the ship steered automatically (obtained from 10 trials with different t_c and t_k : domain of ship waterline shape; assumed normal distribution of waterline positions in relation to X-axis)

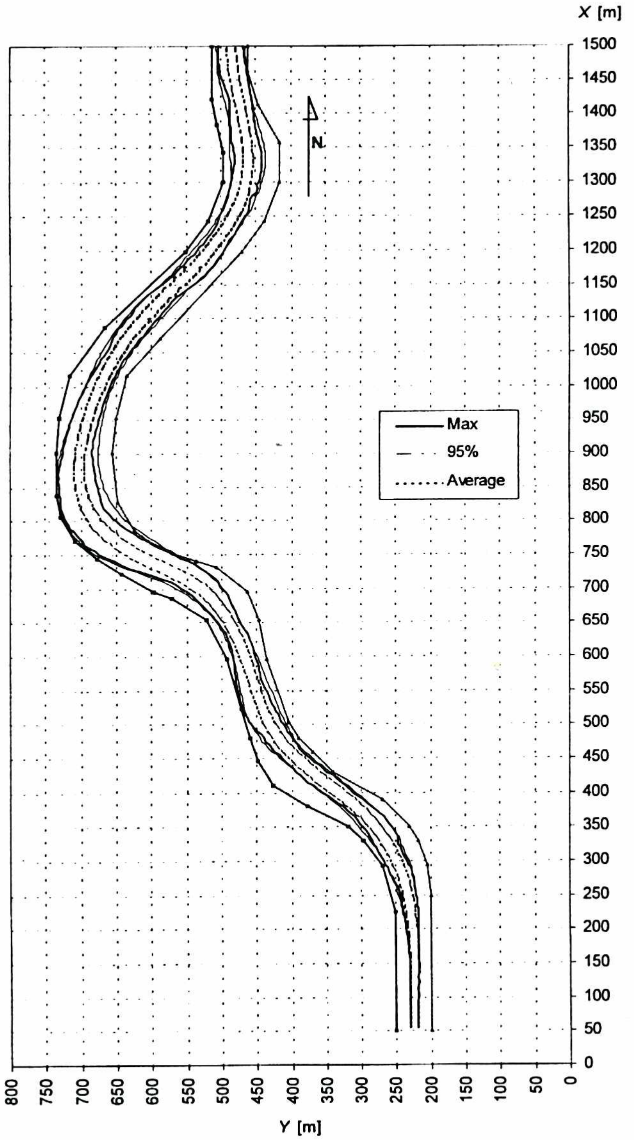

Fig.11. The statistically determined movement area of the ship steered manually (obtained from 10 trials ; assumed normal distribution of waterline positions in relation to X-axis)

CONCLUSIONS

The navigator, while deciding to change ship trajectory (i.e. to perform a manoeuvre), carries out a complex conceptual process taking into consideration all information coming from navigation equipment and his own senses. One of the most important criteria taken by him into consideration is keeping the safe distance to a navigation obstacle. The methods of distance-to-obstacle calculation and of domain designation in limited sea areas, presented in this paper, can be very useful to the navigator who works with the electronic chart in a wheelhouse. The methods also serve as the basis for designing the autonomous model of ship movement, used in simulation research.

Appraised by Stanisław Gucma, Assoc.Prof.,D.Sc.

NOMENCLATURE

a, b	-	axes of an elliptical domain
d	-	ship draught
d_{ah}	-	the distance from ship bow to an ahead obstacle
d_R	-	the minimum distance from a chosen ship waterline point to the restricting line
d_s	-	the assumed safe distance to the manoeuvre area boundary line
i	-	counter of segments of the boundary or restricting line
j	-	counter of segments of the arbitrary domain
t_c	-	time interval between manoeuvre predictions in autonomous model of ship's movement
t_k	-	time duration of manoeuvre prediction in autonomous model of ship movement
B	-	ship breadth
L	-	ship overall length
$P_D(x_D, y_D)$	-	the foremost ship-waterline contour point of co-ordinates x_D, y_D
$P_i(x_i, y_i)$	-	point of the line restricting the manoeuvre area, of co-ordinates x_i, y_i
$P_j(x_j, y_j)$	-	point of the arbitrary domain, of co-ordinates x_j, y_j
$P_{Pi}(x_{Pi}, y_{Pi})$	-	point of intersection of the course line with a line passing through i-th segment of the restricting line, of co-ordinates x_{Pi}, y_{Pi}
$P_{PPi}(x_{PPi}, y_{PPi})$	-	point of the orthogonal projection of a chosen ship waterline point onto the line containing *i-th* segment of the restricting line
$P_S(x_S, y_S)$	-	the centre of ship-waterline point of co-ordinates x_S, y_S
ΔKR	-	angle of turn at curved segment of the fairway (ΔKR=ΔCOG)
ϕ	-	the angle between x-cooridinate axis and the radius-vector of the ellipse point (x,y)

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Conference

Computer systems in machine construction and exploitation

On 27 January 2000 the first-of- the-year meeting of the Regional Group of the Utility Foundations Section (SPE), Mechanical Engineering Committee (KBM), Polish Academy of Sciences (PAN), was held at the Institute of Fluid Flow Machinery (IMP -PAN) in Gdańsk.

During its seminar part under the heading : „Computer systems in machine construction and exploitation" 6 papers were presented which dealt with selected research projects carried out by the Institute, namely :

- *Computer systems in construction and exploitation of machines – Present state and development prospects* (by Prof., J. Kiciński)
- *Genetic algorithms and vibration methods in detecting the failed machine elements* (by Prof., M. Krawczuk, Prof., W. Ostachowicz, and A. Żak, D.Sc.)
- *Flow tests of turbine blade systems with the aid of CFD* (by P. Lampart, D.Sc.)
- *Maps of pin positions within bearings due to dynamic behaviour of a large rotor machine* (by S. Banaszek, M.Sc.)
- *Energy and diagnostic tests of hydro-electric generating sets in Polish water power plants* (by J. Steller, D.Sc.)
- *Laser diagnostics of flow* (by M. Kocik, M.Sc.)

After discussion on the papers, the other part of the meeting was devoted to presentation (by Prof. Kiciński) of the Regional Group report on its activity in the period of 1997 ÷ 1999, and to election of its new authorities for 2000 ÷ 2002 term. Prof. J. Kiciński (IMP-PAN) was again elected to the chairmanship of the Group., and Mrs.M.Bagińska (IMP-PAN) will continue to serve as its secretary.