JÓZEF LISOWSKI, Prof.,D.Sc.,E.E.
Gdynia Maritime Academy
Faculty of Electrical Marine Engineering
Department of Ship Automation

Computational intelligence methods in the safe ship control process

SUMMARY

The paper presents a synthesis of multistage ship's optimum control by the application of the dynamic programming to determine own ship's safe trajectory during passing other ships. The Bellman's functional equation for the control process of the own ship is given. The state constraint variables, in the form of a circle, parabola, ellipse or hexagon, formulated by neural networks as the encountered ship's domain, are put into the computer program as a separate procedure.

The considerations are illustrated by examples of computer simulation by a PROGNEURAL programme for determination of the safe ship's trajectory in situations of passing a number of the objects recorded on the ship radar screen in real navigation situations at sea.

INTRODUCTION

The problem of collision avoidance has become an urgent issue, therefore it is necessary to describe the process of collision avoidance more accurately. A contemporary tendency in the domain of ship control concerns automation process of choosing optimum manoeuvre or optimum safe trajectory based on the information from the anticollision system ARPA (Automatic Radar Plotting Aids). The ARPA system enables to automatically track at least $j = 20$ objects encountered, to determine their movement parameters (speed V_j and course ψ_j) and elements indicating their approaching the own ship, D^j_{min} (Distance of the Closest Point of Approach) and T^j_{min} (Time to the Closest Point of Approach), together with the risk of collision r_j. However, the operational range of a standard ARPA system ends up with the simulation of a manoeuvre selected by navigator.

In this paper the solution is discussed of the basic task of determining the ship position in every stage of ship trajectory, based on a model of kinematics and dynamics of the process. It is assumed that the motion of encounter targets is straight-line and uniform. Safe ship steering depends on continuous observation of the situation at sea, determination of the anticollision manoeuvre, realisation of it and safe travel to the aim point. So it is important to determine safe trajectory of ship as a sequence of manoeuvres (of ship's course and/or speed) in a multistage decision making process (Fig.1).

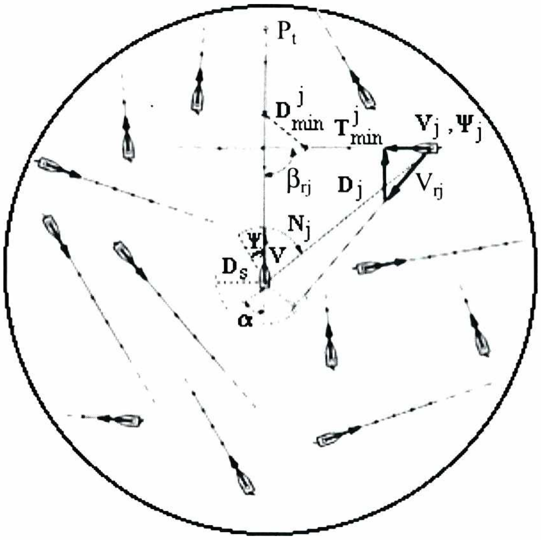

Fig. 1. The multistage process of a safe passing of the own ship during encounter of j ships

The synthesis of multistage safe ship control is a highly complex steering process problem of dynamic, non-linear, multi-dimensional, non-stationary and game controlling features. In practice methods of selecting a manoeuvre or trajectory assume the form of relevant controlling algorithms programmed in the microprocessor controller generating the option of the ARPA anti-collision system or of the training simulator [9].

The mode of steering of a ship depends on the range of precision of the information on the current navigational situation and on the adopted model of the process.

During the development of the process the following elements are to be considered : equations of kinematics and dynamics of own ship, disturbances due to sea waves, wind and sea currents, navigational constraints, strategy of the encountered objects, and the control objective function.

A wide variety of models possible to be adopted directly influences the synthesis of relevant algorithms of control, and then the effects of safe steering of own ship.

STATE EQUATIONS

A specific nature of the process of ship steering under collision situations may be characterized by : high alterations of the course (within the range of $20^o \div 90^o$), reduction of speed (by not more than 30%). At the conditions the model of ship's dynamics may be presented in the form given in Fig.2.

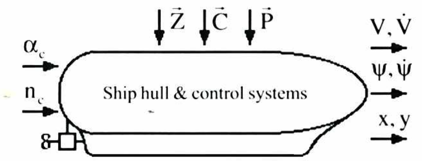

Fig.2. Ship as an object of control

The ship's motion is described by :

α_c – commanded rudder angle
n_c – commanded rotational speed of screw propeller
V – speed
$\dot{V}$ – acceleration
ψ – heading (course)
$\dot{\psi}$ – angular turning speed
(x,y) – position (atitude and longitude, respectively)
$\vec{Z}$ – vector of disturbances
$\vec{C}$ – vector of constraints (j encountered objects)
$\vec{P}$ – vector of dynamic parameters.

Simplifications with regard to a precise model of the ship dynamics cover :

- the omission of the drift angle and reduction of the ship's speed during the manoeuvre
- the adoption of a non-linear mathematical description of the ship's dynamic features in the rudder control system (according to Nomoto) and the linear one in the control system of the rotational speed of the propeller [8].

The description of the ship's dynamics makes it possible to represent the state equations in a discrete form as follows :

$$\left.\begin{array}{c}
x_{k+1} = x_k + V_k \cdot \Delta t_{k+1} \cdot \sin\psi_k \\
y_{k+1} = y_k + V_k \cdot \Delta t_{k+1} \cdot \cos\psi_k \\
\psi_{k+1} = \psi_k + \psi_k \cdot \Delta t_{k+1} \\
\psi_{k+1} = \psi_k + \dfrac{1}{T_1}(-\psi_k - a_1 \cdot \psi_k \psi_k + \\
+ a_2 \cdot \alpha_{c,k})\Delta t_{k+1} \\
V_{k+1} = V_k + \dot{V}_k \cdot \Delta t_{k+1} \\
\dot{V}_{k+1} = \dot{V}_k + \dfrac{1}{T_2 \cdot T_3}[-(T_2 + T_3)\dot{V}_k - V_k + \\
+ a_3 \cdot n_{c,k}]\Delta t_{k+1} \\
t_{k+1} = t_k + \Delta t_{k+1}
\end{array}\right\} \qquad (1)$$

The identification research conducted with regard to a few types of the cargo vessels under regular operational conditions at various speeds and loading states makes the following assessment of some values of the above given model possible :

time constants :

$$T_1 = 5 \div 50\ s \qquad T_2 = 10 \div 100\ s \qquad T_3 = 50 \div 500\ s$$

static characteristics coefficients :

$$a_1 = 50 \div 1000\ s/rad \quad a_2 = 0.01 \div 0.3\ 1/s \quad a_3 = 1 \div 10\ m$$

CONTROL AND STATE CONSTRAINTS

The constraints of control and state of the process result from :

⇨ consideration of the physical values characterizing the process :

$$\alpha_c / \alpha_{max} \le 1 \qquad 0 \le n_c / n_{max} \le 1 \qquad (2)$$

$$0 \le \dot{\psi} \le \dot{\psi}_{max} \qquad 0 \le V \le V_{max} \qquad 0 \le \dot{V} \le \dot{V}_{max} \qquad (3)$$

⇨ consideration of real navigational constraints :

$$g_n(x,y) \le 0 \qquad (4)$$

and

⇨ necessity of ensuring the safe shipping, with regard to the recommendations of the regulations on the priority way law of COLREG (International Regulations for Preventing Collisions at Sea) :

$$g_j(x,y,t) \le 0 \qquad (5)$$

where : g - form of constraints.

INITIAL AND FINAL CONDITIONS

In practice the process state is currently controlled by the arrangements of the ARPA anti-collision system (radar, gyrocompass, log, angular and rotational speed indicators). The initial conditions of the process are determined by a variety of Θ_o described during the initiation of the automatic monitoring of the encountered objects by the ARPA system :

$$\Theta_o = (x_o, y_o, \psi_o, V_o, \dot{\psi}_o = \dot{V}_o = t_o = 0) \qquad (6)$$

Two types of control tasks were adopted having regard to the final conditions of Θ_f :

★ steering with a determined final point of the trajectory :

$$P_t = P_t(x_t, y_t) \qquad (7)$$

which corresponds to the situation of the ship's control in restricted waters

★ steering with a determined final course in open waters :

$$\psi_f = \psi_o \qquad \dot{\psi}_f = \dot{V}_f = 0 \qquad V_f = V_o \qquad (8)$$

CONTROL QUALITY INDEX

The basic criterion for the ship's control, contained in the state constraints (5), is to ensure safe passing of the vessels. Moreover, an optimization criterion is taken into account in the form of the smallest possible loss of way for safe passing of the objects, which, at a constant speed of the own ship, leads to the time-optimum control :

$$I(\alpha_c, n_c) = \int_0^{t_K} V\,dt \cong V \int_0^{t_K} dt \to \min \qquad (9)$$

where : I - quality index.

NEURAL SHIP'S DOMAINS

The collision risk area, i.e. *the ship's domain* creates *NEUROCONSTR* procedure in the computer programme [2,3,4,10].

The adopted ship's domain is represented in the form of a circle, parabola, ellipse or hexagon the dimensions of which depend on the relative speed of the object being passed, and the dimensions are modified on the basis of the answer from an appropriately prepared neural network which assesses the collision risk level (Fig.3).

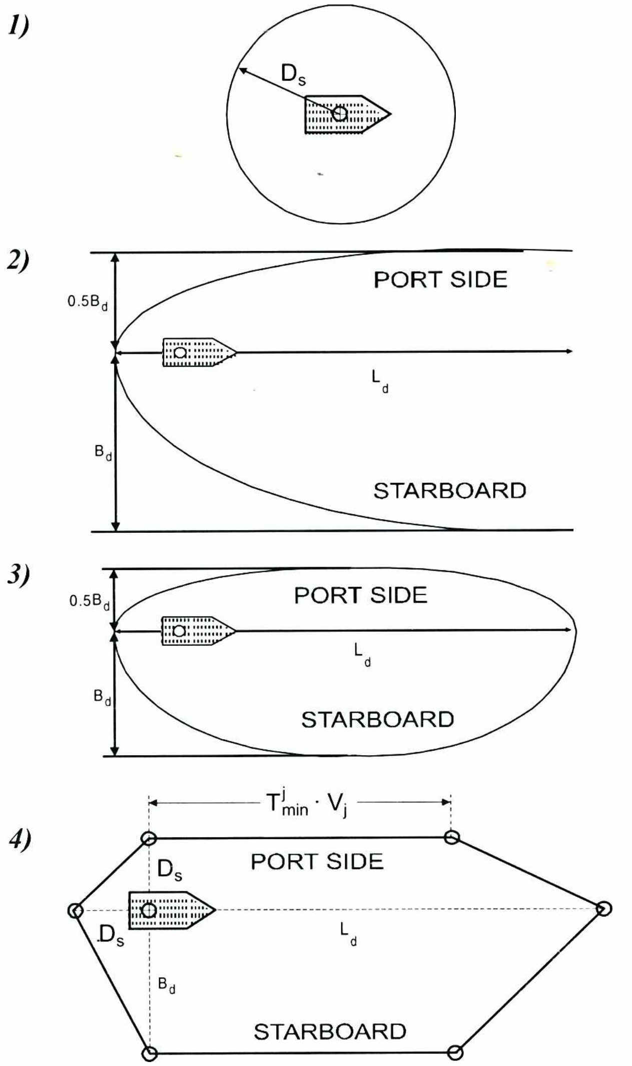

***Fig.3.** The shapes of the neural ship's domains : 1-circle, 2-parabola, 3-ellipse, 4- hexagon*

The safe distance D_s is one of the fundamental factors taken into consideration when ship domain is determined. This is the smallest acceptable distance from the own ship to the navigational obstacle. This parameter is estimated by the navigator on the basis of current navigational situation, and it usually is equal to the D^j_{min} distance (0.5 ÷ 3.0 nm).

The **circular form** of the constraints (5) is defined as the circle of the radius equal to D_s :

$$g^c_j(x_j, y_j) = (x_j^2 + y_j^2) \le D_s^2 \tag{10}$$

where: (x_j, y_j) – j-th object co-ordinates.

The **parabolic form** of constraints (5) is described by equation :

$$\begin{aligned} g^p_j(x_j, y_j) = x_j \sin\psi_j + \\ + y_j \cos\psi_j - \zeta(x_j \cos\psi_j - y_j \sin\psi_j)^2 \le 0 \end{aligned} \tag{11}$$

where :

ψ_j - course of j-th object
ζ - span of the parabola arms.

The **elliptic form** of the constraints (5) is calculated by using formula :

$$\begin{aligned} g^e_j(x_j, y_j) = L_d^2 B_d^2 - (x_j \sin\psi_j + y_j \cos\psi_j - C_d)^2 B_d^2 + \\ - (x_j \cos\psi_j + y_j \sin\psi_j)^2 L_d^2 \le 0 \end{aligned} \tag{12}$$

where :

C_d - focal distance of the ellipse
L_d, B_d - axes of the ellipse (called the *dynamic length and beam of the ship*); they can be computed by using the following formulae :

$$\begin{aligned} L_d &= 1.1L(1 + 0.345V^{1.6}) \\ B_d &= 1.1(B + 0.767LV^{0.4}) \end{aligned} \tag{13}$$

where :

L, B - length and beam of the ship, respectively
V - ship velocity.

The basic parameter of the **hexagonal domain** is the distance between the centre point of the ship and bow-point of the domain, equal to L_d. The detail equations for computing the hexagon dimensions can be found in [13].

Let's consider a network of five inputs and one output whose aim is to ascribe, with the smallest possible error, one of the acceptable values of the responses to particular input vectors [5,6,7]:

$$z = \mathbf{\Gamma}[\Omega \cdot \mathbf{m}] \tag{14}$$

$$\mathbf{m} = [P_j \ \beta_{rj} \ V \ V_j \ |V_{rj}|] \tag{15}$$

$$z = [0 \ 1] \tag{16}$$

and the following is to be found :

$$\min_{\Gamma}\{\Sigma(z_k - z_{ek})^2\} \tag{17}$$

where :

Γ - activation functions of neural network layers
Ω - vector of coefficients of neural network
m - network inputs
P_j - position of j-th object
β_{rj} - relative course of j-th object
V - speed of the own ship
V_j - speed of j-th object
$|V_{rj}|$ - relative speed
z_k - network response
z_{ek} - expected network response
k - index of the time moment (Fig.4).

The values of the elements of the x_k vector are provided from the ARPA system, and the z_k values determine the collision risk level through the dimension of the domain attributed to j-th object (Table).

Subordination of the neural network outputs

z_{ek}	**Description**
0.1	safe situation
0.3	attention
0.5	risk
0.7	situation decidedly dangerous
0.9	collision

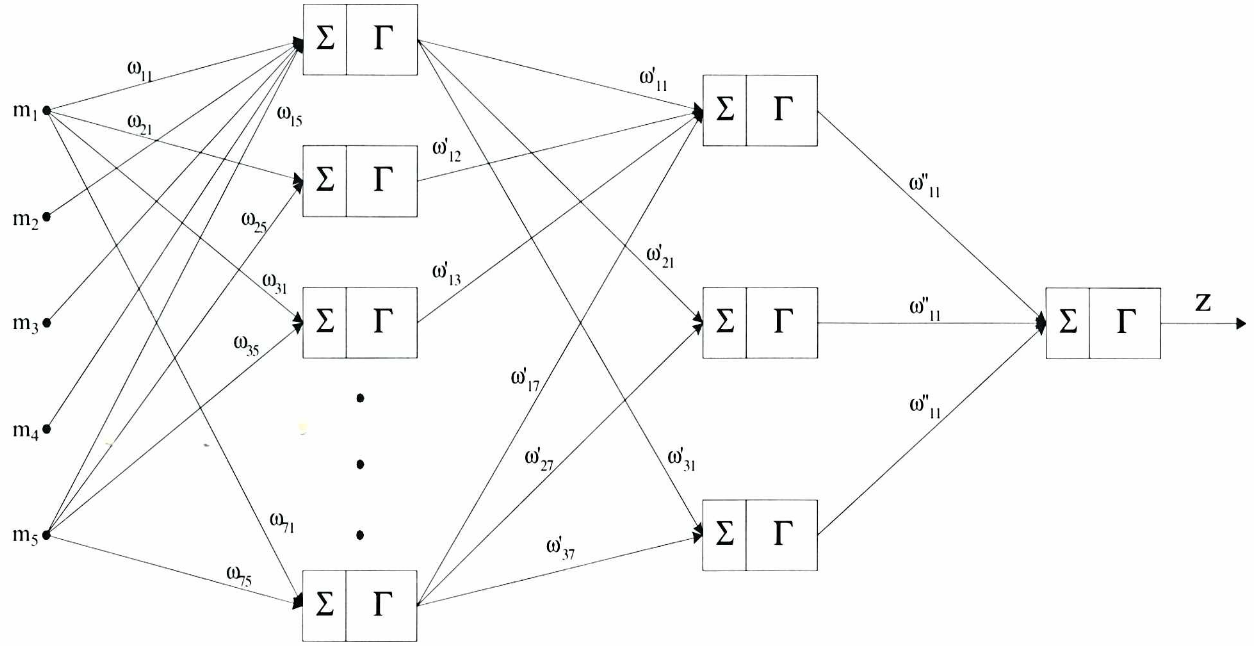

Fig.4. *The structure of the neural network generating the ship's domains*

The neural network undergoing the learning process classifies the hyperspace of the parameters of the navigational situation by subordinating a value of the collision risk coefficient, in the form of a number from the range of $0.1 \div 0.9$, to each point of this hyperspace.

The one-way network has three layers of neurons. The non-linear activation functions in the first and second layers represent a tangent nature and the output layer represent the sigmoidal nature.

The network was modelled with the use of Neural Network Toolbox from the MATLAB package.

The learning process used the algorithm of the back-propagation of the error with adaptive learning rate and the *momentum*. The learning data were prepared by simulating navigational situations and recording corresponding expected network answers given by an experienced navigator.

THE INTERNATIONAL REGULATIONS FOR PREVENTING COLLISIONS AT SEA (COLREG RULES)

The incorporation of the maritime navigation COLREG rules into the mathematical model is effected in the following manner :

- in good visibility conditions the selection of the alternate manoeuvre depends on the angle β_{rj} (Fig.1). At its value of :

  $$0 \le \beta_{rj} \le 180^{\circ} \qquad (18)$$

  the own ship encounters the object from starboard, whilst for :

  $$-180^{\circ} \le \beta_{rj} < 0 \qquad (19)$$

  an encounter happens with the object from port side. According to the COLREG rules the own ship must give way to the objects which are approaching from starboard. The conditions (18) and (19) are implemented into the NEUROCONSTR procedure by adequate formulation of the constraints (5) :

  - for angle β_{rj} satisfying condition (19) a circle constraint is imposed
  - for objects appearing on the starboard the condition (18) in the form of a parabola, ellipse or hexagon seems the most adequate

- in restricted visibility conditions the starboard rule giving way to the object approaching from starboard does not apply, but the own ship must keep a greater safe approach distance of $D_s = 2 \div 3$ nm.

DYNAMIC PROGRAMMING OF SAFE TRAJECTORY

The optimum control of the ship in terms of an adapted index of the control quality may be determined by applying Bellman's principle of optimization.

The principle describes the basic feature of the optimum strategy :

whatever are the initial state and decisions
the remaining decisions must generate the optimum strategies
from the point of the state resulting from the first decision.

Hence it results that the calculations by using this method are usually initiated from the final stage and then the process goes toward the first one [1].

In a work mentioned in [8] it was demonstrated that the process of the collision prevention fulfils the duality conditions, therefore the optimum trajectory of the ship under a collision situation is determined by using the optimization principle and is commenced from the calculation of the first stage and then it is directed toward the final stage.

The optimum time for the ship to go through k stages is as follows :

$$\left.\begin{aligned} t_k^* = \min_{\alpha_{c,k-2},n_{c,k-2}} \{ & t_{k-1}^*[x_k, y_k, \psi_{k-1}, \dot{\psi}_{k-1}, \\ & V_{k-1}, \dot{V}_{k-1}] + \Delta t_k [x_k, y_k, x_{k+1}(x_k, \psi_k(\psi_{k-1}, \\ & \dot{\psi}_{k-1}(\dot{\psi}_{k-2}, \alpha_{c,k-2}, \Delta t_{k-2}), \Delta t_{k-1}), \\ & V_k(V_{k-1}, \dot{V}_{k-1}, (\dot{V}_{k-2}, n_{c,k-2}, \Delta t_{k-2}) \Delta t_{k-1})), \\ & y_{k+1}(y_k, \psi_k(\psi_{k-1}, \dot{\psi}_{k-1}(\dot{\psi}_{k-2}, \alpha_{c,k-2}, \\ & \Delta t_{k-2}, \Delta t_{k-1}) V_k(V_{k-1}, \dot{V}_{k-1}(\dot{V}_{k-2}, n_{c,k-2}, \\ & \Delta t_{k-2}), \Delta t_{k-1})), V_k(V_{k-1}, \dot{V}_{k-1}(\dot{V}_{k-2}, \\ & n_{c,k-2}, \Delta t_{k-2}), \Delta t_{k-1})]\} \end{aligned}\right\} \qquad (20)$$

$$k = 3, 4, \ldots, K$$

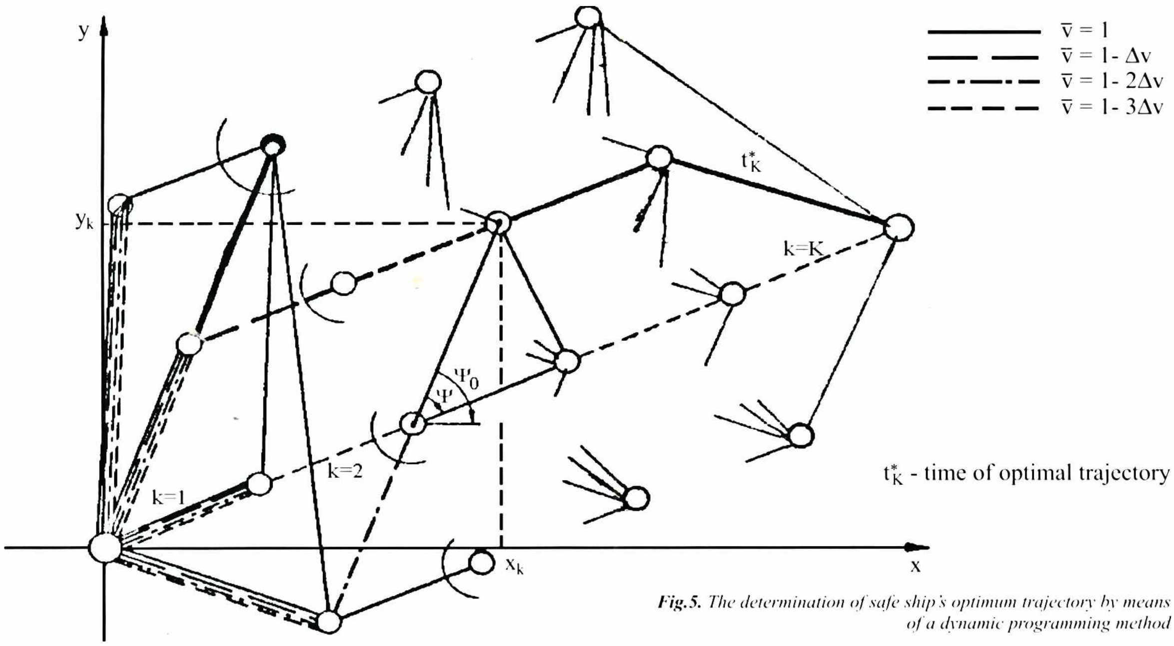

***Fig.5.** The determination of safe ship's optimum trajectory by means of a dynamic programming method*

That optimum time is a function of the system state at the end of the (k-1) stage and control values $(\alpha_{c,k-2}, n_{c,k-2})$ at the (k-2) stage.

By going from the first stage to the last one the formula (20) determines the Bellman's functional equation for the process of the ship's control by the alteration of the rudder angle and the rotational speed of the propeller.The constraints for the state variables and the control values (2)÷(5) generate the *NEUROCONSTR* procedure in the *PROGNEURAL* computer algorithm for the determination of the safe ship's trajectory (Fig.5).

The consideration of the constraints resulting from maintaining the safe approaching distance and the recommendations of the way priority law is performed by checking whether the state variables have not exceeded the constraints in each of the considered intersections and by rejecting the intersections in which the exceedance has occurred [11,12].

COMPUTER SIMULATION

The trajectories were computed by means of the *PROGNEURAL* programme for the own ship, 12,000 dwt container carrier, in situations recorded in the Thames Estuary and English Channel regions, both for good and poor visibility at sea. At every step of calculations the values of the domains were updated (Fig.6 and 7 at the end of the paper).

CONCLUSIONS

The presented synthesis of the steering process together with the algorithms for the optimum control determination form a basis for developing a computer programme for defining the safe trajectory of a ship with the use of information from the on-board anticollision system.

The safe trajectory proposal can be simulated on the display of ARPA anti-collision system as an additional feature of the system. The navigator is thus supported in the control of the process of generating and evaluating various options of efficient decision.

The presented neural networks may be used as the elements of the systems for the assessment of the safety of the passing ships due to making current correction of the sizes of ships' domains possible. The networks are able to represent the heuristic knowledge similar to that of an experienced navigator.

Acknowledgement

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NOMENCLATURE

D - distance
N - bearing
$P_t(x_t, y_t)$ - point of trajectory
t - time
β_r - relative course
Θ - symbol of conditions
ω - neuron network coefficient

Indices

c - commanded
f - of final conditions
j (upper or lover) - of encountered object
k - calculation step, k=1,...,K
n - of navigation
o - of initial conditions
r - relative
s - save
- (upper) - relative value

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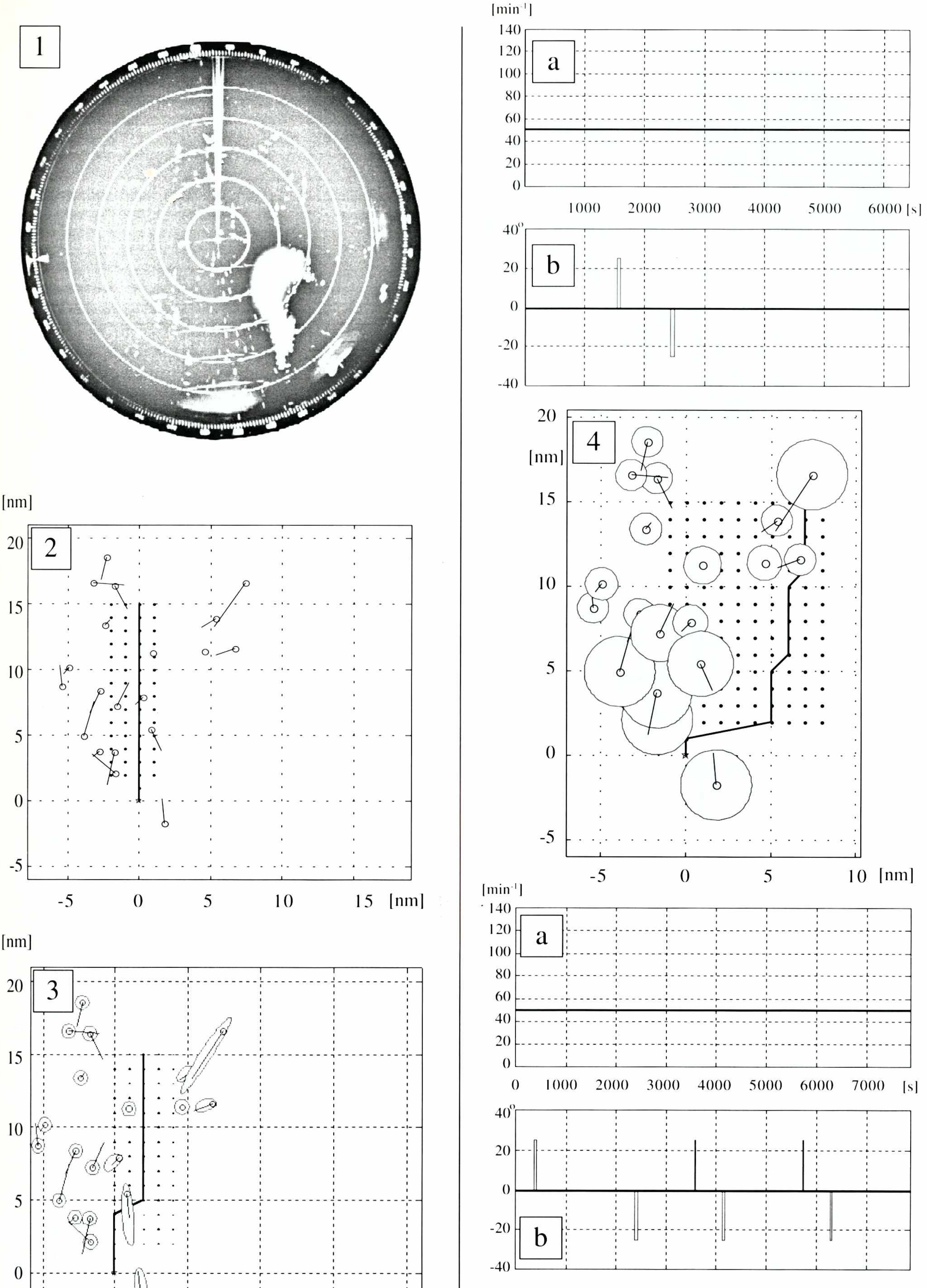
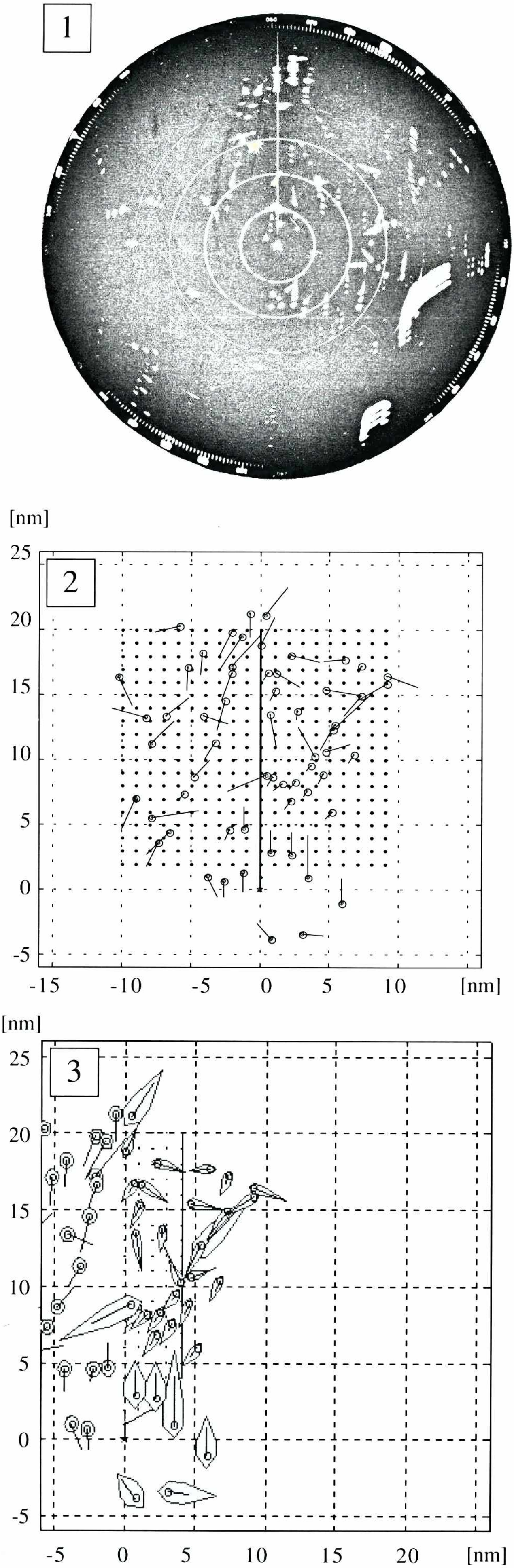


Fig.6. Computer simulation results of the own ship's safe trajectory in the situation of 20 encountered objects
1 - radar image of the situation in the Thames Estuary
2 - vectors of the own ship and met objects
3 - safe trajectory at good visibility (D_s=0.5 nm)
4 - safe trajectory at poor visibility (D_s=1.5 nm)
a - rotational speed of propeller, b - rudder angle



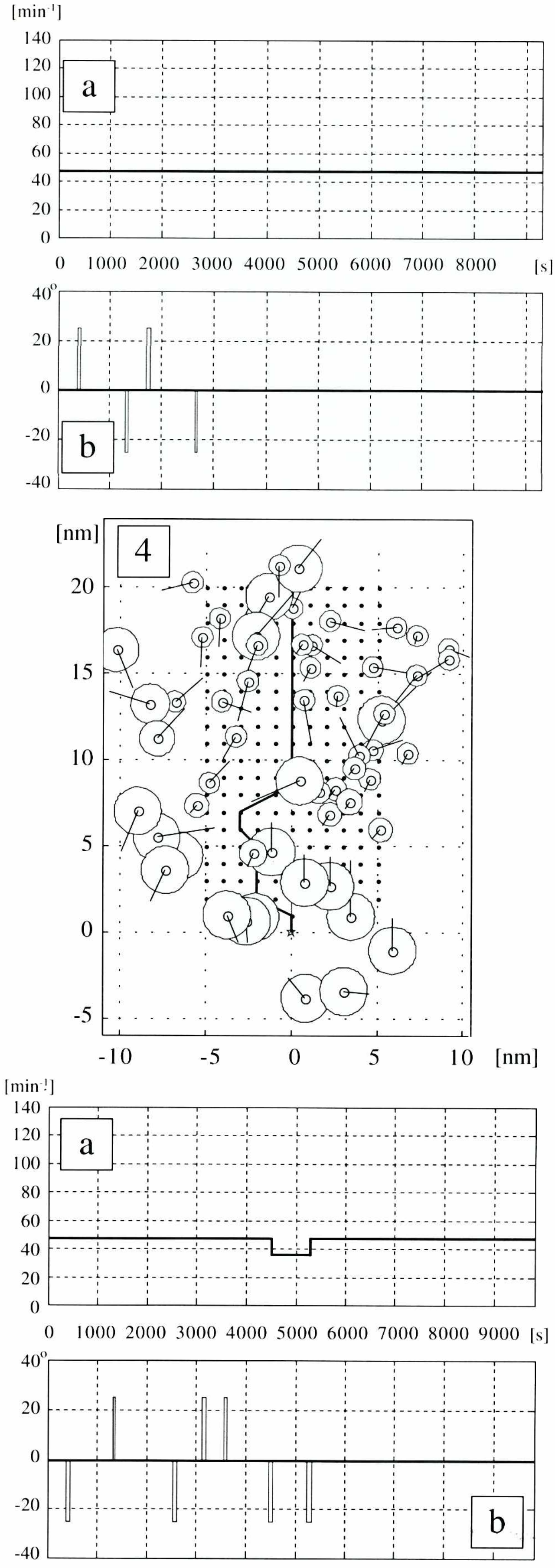


Fig. 7. *Computer simulation results of the own ship's safe trajectory in the situation of 60 encountered objects*
1- *radar image of the situation in the English Channel area*
2 - *vectors of the own ship and met objects*
3 - *safe trajectory at good visibility* (D_s*=0.5 nm)*
4- *safe trajectory at poor visibility* (D_s*=2.0 nm)*
a - *rotational speed of propeller,* ***b*** - *rudder angle*