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Dynamic optimisation of safe ship trajectory with neural representation of encountered ships

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Abstract

This paper describes an application of the dynamic programming method to determine the safety of one's own ship trajectory during encounter of other ships. A dynamic model of the process, with kinematic constraints of state and determined by a three-layer artificial neural network has been used for the development of control procedures. Non-linear activation functions in the first and second layers may be characterised by a tangent curve while the output layer is of a sigmoidal nature. The Neural Network Toolbox of the Matlab software has been used to model the network. The learning process used an algorithm of backward propagation of the error with an adaptively selected learning step. The considerations have been illustrated through an example implemented in a computer simulation using the algorithm for the determination of the safe ship trajectory in situations of encounter of multiple ships, recorded on the ship's radar screen in real navigational situation in the Kattegat Strait.

Introduction

Safe ship navigation is one of the most important problems in marine navigation. It is difficult to make correct decisions during a collision situation because of the growing size, velocity and number of ships that are taking part in maritime transport. At the same time, there is a tendency in the domain of ship control towards automation of processes for choosing optimal manoeuvres or safe trajectories based on the information from the anti-collision system ARPA (Automatic Radar Plotting Aids). The ARPA system enables to automatically track at least $j = 20$ ships encountered, to determine their movement parameters (speed V_j and course ψ_j) and elements indicating their closing to one's own ship (D_{CPAj} – Distance of the Closest Point of Approach and T_{CPAj} – 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 (Bist, 2000; Kouemou, 2009).

Multistage safe ship control

Safe ship control depends on continuing observation of the situation at sea, determination and realisation of the anti-collision manoeuvre, and safe travel to the destination point. It is therefore important to determine the safe trajectory of a ship as sequence of single manoeuvres, and course and/or speed as a multistage decision-making process (Wiśniewski, 2011).

The problem of the development of the multistage control process is very difficult, considering the high complexity of steering, which has dynamic, non-linear, multi-dimensional, non-stationary and game controlling features. In practice, the methods for the selection of 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 (Cross, 1994; Modarres, 2006).

The steering mode 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 relevant elements are to be considered: equations of kinematics and dynamics of the ship, disturbances generated by the sea's wave motion as well as wind and sea currents, navigational constraints, strategy of the encountered objects and the purpose of the control. A wide variety of models directly influence the synthesis of various algorithms of control and the effects of safe steering (Leondes, 1998).

Model of control process

A ship's steering under collision situations may be characterised by high alterations of the course, within the range 20°–90°, and reduction of speed by not more than 30%. The model of the ship's dynamics may be presented as in Figure 1.

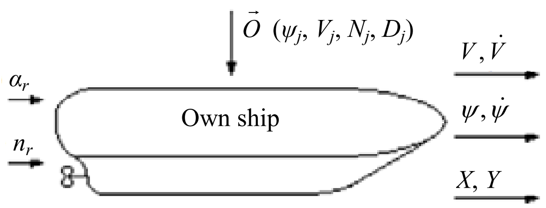

Figure 1. Ship as object of control: α_r – reference rudder angle, n_r – reference rotational speed of screw propeller, ψ – course, $\dot{\psi}$ – turning speed, V – speed, $\dot{V}$ – acceleration, (X,Y) – position, $\vec{O}$ – constraints as encountered j ship: ψ_j – course, V_j – speed, N_j – bearing, D_j – distance

The simplifications introduced in the model of the ship's dynamics include the omission of the drift angle and fall in 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 a linear model for the control system of the rotational speed of the propeller.

State process equations

The description of the ship's dynamics can be represented by the following state equations:

$$\left.\begin{aligned} x_{1,k+1} &= x_{1,k} + x_{5,k}\cdot\Delta t_{k+1}\cdot\sin x_{3,k} \\ x_{2,k+1} &= x_{1,k} + x_{5,k}\cdot\Delta t_{k+1}\cdot\cos x_{3,k} \\ x_{3,k+1} &= x_{3,k} + x_{4,k}\cdot\Delta t_{k+1} \\ x_{4,k+1} &= x_{4,k} + \frac{1}{T_1}(-x_{4,k} - a_1\cdot x_{4,k}\left|x_{4,k}\right| + \\ &\quad + k_1\alpha_{\max}\cdot u_{1,k})\Delta t_{k+1} \end{aligned}\right\} \quad (1a)$$

$$\left.\begin{aligned} x_{5,k+1} &= x_{5,k} + x_{6,k}\cdot\Delta t_{k+1} \\ x_{6,k+1} &= x_{6,k} + \frac{1}{T_2T_3}[-(T_2+T_3)x_{6,k} - x_{5,k} + \\ &\quad + k_2\cdot n_{\max}\cdot u_{2,k}]\Delta t_{k+1} \\ x_{7,k+1} &= x_{7,k} + \Delta t_{k+1} \end{aligned}\right\} \quad (1b)$$

where $x_1 = X$; $x_2 = Y$; $x_3 = \psi$; $x_4 = \dot{\psi}_{\max}$; $x_5 = V$; $x_6 = \dot{V}$; $x_7 = t$; $u_1 = \alpha_r / \alpha_{\max}$; $u_2 = n_r/n_{\max}$; a_1, k_1, k_2 – gain coefficients; T_1, T_2, T_3 are time constants.

The identification research conducted with regards to a few types of cargo vessels under regular operational conditions at various speeds and loading states allows for the following assessment of the values of the parameters present in the above model: T_1 = 5÷50 s, T_2 = 10÷100 s, T_3 = 50÷500 s, a_1 = 50÷1000 s/rad, k_1 = 0.01÷0.3 1/s, k_2 = 1÷10 m.

Control and state constraints

The constraints of control and the state of the process are a result of the necessity to consider the physical values characterising the process:

$$u_1 \le 1,\ 0 \le u_2 \le 1 \quad (2)$$

$$0 \le x_4 \le \dot{\psi}_{\max},\ 0 \le x_5 \le V_{\max},\ 0 \le x_6 \le \dot{V}_{\max} \quad (3)$$

and the consideration of real navigational constraints:

$$g_n(x_1, x_2) \le 0 \quad (4)$$

At the same time, to ensure safe shipping it is necessary to consider the recommendations of the international regulations on the priority way, COLREG (Collision Regulations). In accordance with regulation 17, and in conditions of good visibility at sea, the way of the vessel approaching from the right subsists:

$$g_j(\psi_j, V_j, N_j, D_j) \le 0 \quad (5)$$

Control quality index

The basic quality index the ship's control is to ensure safe passing of the encountered ships, which is considered in the state constraints of Eq. (5). Moreover, a goal function for optimisation is taken into consideration in the form of the smallest possible way loss required for safe passing of the encountered ships, which, for a constant speed of one's own ship, leads to the time-optimal control:

$$I(u_1, u_2) = \int_0^{t_k} x_5 \, \mathrm{d}t \cong x_5 \int_0^{t_k} \mathrm{d}t \rightarrow \min \quad (6)$$

Neural representation of encountered ships

Ships domains

The areas in which the risk of collision exists, known as the *encountered ships domains,* are created in the *neural constraints* computer programme procedure (Colley, Curtis & Stockel, 1983; Dovie, Dove & Stockel, 1980). The adopted ships' domains are represented as a circle, in conditions of restricted visibility, and, in conditions of good visibility, in the form of a circle for ships on the left side and of a parabola, ellipse, or hexagon, for ships on the right side. The dimensions of domains depends on the relative speed of the ship being passed and are modified on the basis of the answer from an appropriately prepared neural network which assesses the degree of the collision risk (Figure 2).

One of the fundamental factors to be taken into consideration when the ship's domain is determined is the safe distance, D_s. This is the smallest acceptable distance between the ship and the navigational obstacle. This parameter is estimated by the navigator based on the current navigational situation and is usually equal to the D_{CPAj} distance (0.5–3.0 Nm) (Goodvin, 1975).

For a comparative analysis, different domain shapes are assumed. The circle domain (5) is formulated as a circle with radius equal to D_s:

$$g_j^c(X_j, Y_j) = X_j^2 + Y_j^2 - D_s^2 \le 0 \quad (7)$$

where (X_j, Y_j) are the co-ordinates of the *j-th* encountered ship.

The parabolic form of constraint (5) is described by the equation:

$$g_j^p(X_j, Y_j) = X_j \sin\psi_j + Y_j \cos\psi_j + \\ -\zeta(X_j \cos\psi_j - Y_j \sin\psi_j - D_s)^2 \le 0 \quad (8)$$

where ψ_j is the course of the *j-th* encountered ship, and ζ is the span of the parabola arms.

The elliptic form of constraint (5) is calculated using formula:

$$g_j^e(X_j, Y_j) = (X_j \sin\psi_j + Y_j \cos\psi_j - C_{dj})^2 B_{dj}^2 + \\ + (X_j \cos\psi_j + Y_j \sin\psi_j)^2 L_{dj}^2 - B_{dj}^2 L_{dj}^2 \le 0 \quad (9)$$

where C_{dj} is the focal distance of the ellipse, L_{dj}, B_{dj} are the axes of the ellipse that are called *dynamic length beam* of the ship and can be computed using:

$$L_{dj} = 1.1L(1 + 0.345V^{1.6}), \; B_{dj} = 1.1(B + 0.767LV^{0.4}) \quad (10)$$

In equations (10), L and B denote the length and beam of the ship, and V is the ship velocity. The basic parameter of the hexagon shape domain is the distance between centre point of ship and bow-point of the domain, L_{dj}.

Neural ships domains

We now consider a network that has five inputs and one output, with the aim of identifying one of the acceptable values of the response, with the smallest error possible, to particular input vectors:

$$\mathbf{y} = \mathbf{\Gamma}\,[W\,\mathbf{x}] \quad (11)$$

$$\mathbf{x} = [P_j \psi_{wj} V, \; V_j |V_{wj}|] \quad (12)$$

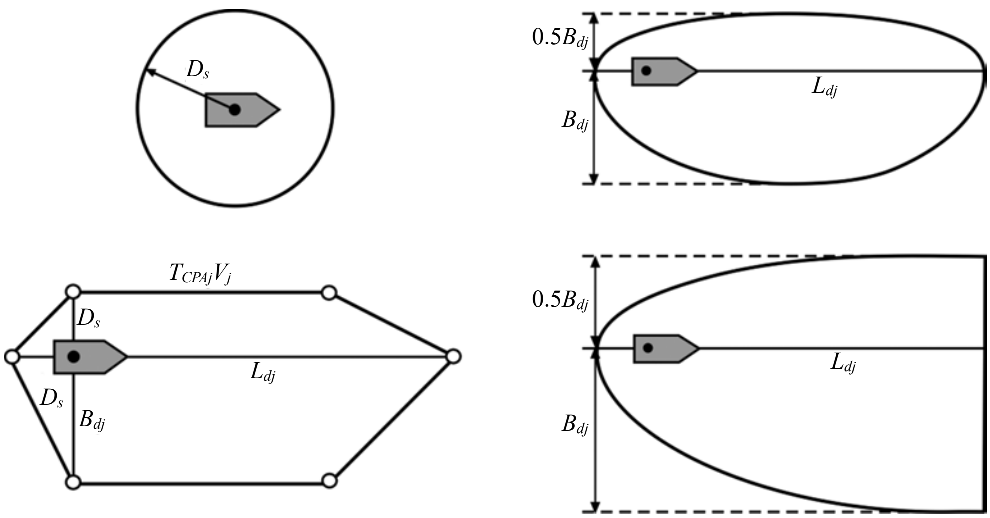

Figure 2. Shapes of domains of neural encountered ships

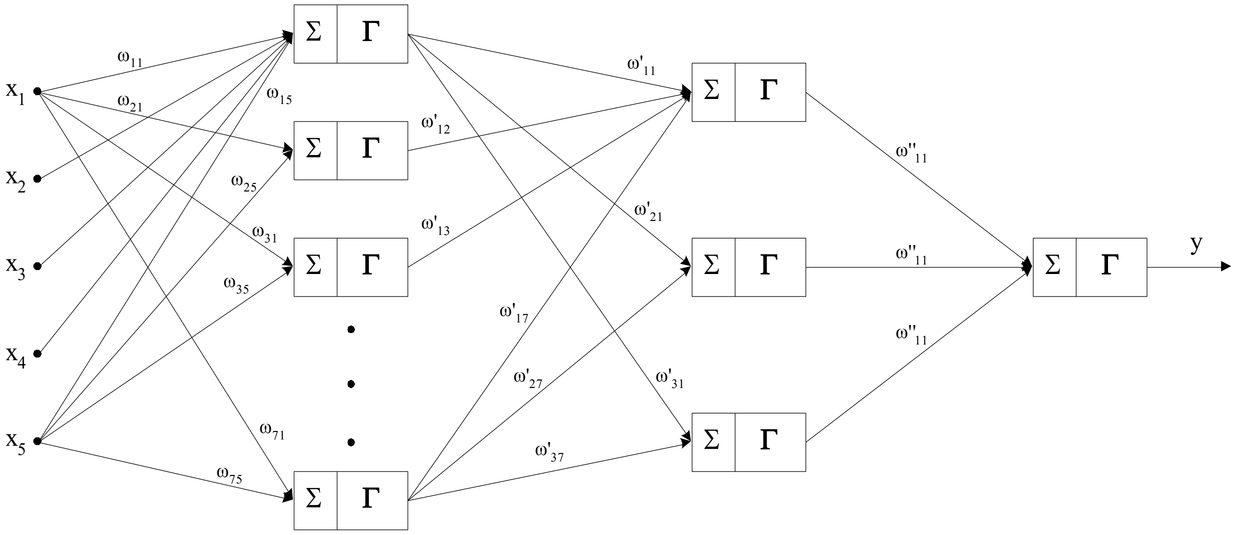

Figure 3. The structure of the neural network generating the ships domains

$$\mathbf{y} = [0{,}1 – \text{safe situation; } 0{,}3 – \text{attention; } 0{,}5 – \text{risk of collision; } 0{,}7 – \text{dangerous situation; } 0{,}9 – \text{collision}] \tag{13}$$

the following result is found:

$$\min_{\Gamma} \{\Sigma(y_k - y_{ek})^2\} \tag{14}$$

where y_k is the network response, y_{ek} is the expected network response, **Γ** the activation functions of neural network layers, P_j the position of the *j-th* encountered ship, V_j the speed of the *j-th* encountered ship, V the speed of one's own ship, ψ_{wj} the relative course of the *j-th* encountered ship, $|V_{wj}|$ the relative speed, and k the index of time moment (Figure 3).

The values of the elements of the x_k vector are provided from the ARPA system, and the y_k values determine the degree of the collision risk through the dimension of the domain assigned to the *j-th* encountered ship (Hertz, Krogh & Palmer, 1991; Hunt, Irwin & Warwick, 1995).

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 represents the sigmoidal nature. The network was modelled with the use of the 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.

Dynamic optimisation of safe trajectory

The determination of the optimal control of the ship in terms of an adopted index of the control quality may be performed by applying Bellman's principle of optimisation. The principle describes the basic features of the optimal strategy – whatever the initial state and decisions are, the remaining decisions must generate the optimal strategies from the point of the state resulting from the first decision. It results from this that the calculations using this method are usually initiated from the final stage and then the process goes toward the first one (Bellman, 1957).

The process of the collision prevention fulfils the duality conditions, therefore the optimal trajectory of the ship under a collision situation is determined using the optimisation principle and is commenced from the calculation of the first stage and is then directed toward the final stage (Lew & Mauch, 2007).

The optimal time for the ship to go through k stages is determined as follows (Eq. 15):

$$\left.\begin{array}{l} t_k^* = \min\limits_{u_{1,k-2},u_{2,k-2}} \{t_{k-1}^*[x_{1,k}, x_{2,k}, x_{3,k-1}, x_{4,k-1}, x_{5,k-1}, x_{6,k-1}] + \Delta t_k [x_{1,k}, x_{2,k}, x_{1,k+1}(x_{1,k}, x_{3,k}(x_{3,k-1}, x_{4,k-1} \\ \quad (x_{4,k-2}, u_{1,k-2}, \Delta t_{k-2}), \Delta t_{k-1}), x_{5,k}(x_{5,k-1},\ x_{6,k-1}, (x_{6,k-2}, u_{2,k-2}, \Delta t_{k-2})\Delta t_{k-1})), \\ \quad x_{2,k+1}(x_{2,k}, x_{3,k}(x_{3,k-1}, x_{4,k-1}(x_{4,k-2}, u_{1,k-2}, \Delta t_{k-2}, \Delta t_{k-1})x_{5,k}(x_{5,k-1}, x_{6,k-1}(x_{6,k-2}, u_{2,k-2}, \\ \quad \Delta t_{k-2}), \Delta t_{k-1})), x_{5,k}(x_{5,k-1}, x_{6,k-1}(x_{6,k-2}, u_{2,k-2}, \Delta t_{k-2}), \Delta t_{k-1})]\} \\ \qquad\qquad k = 3,4,\ldots,K \end{array}\right\} \tag{15}$$

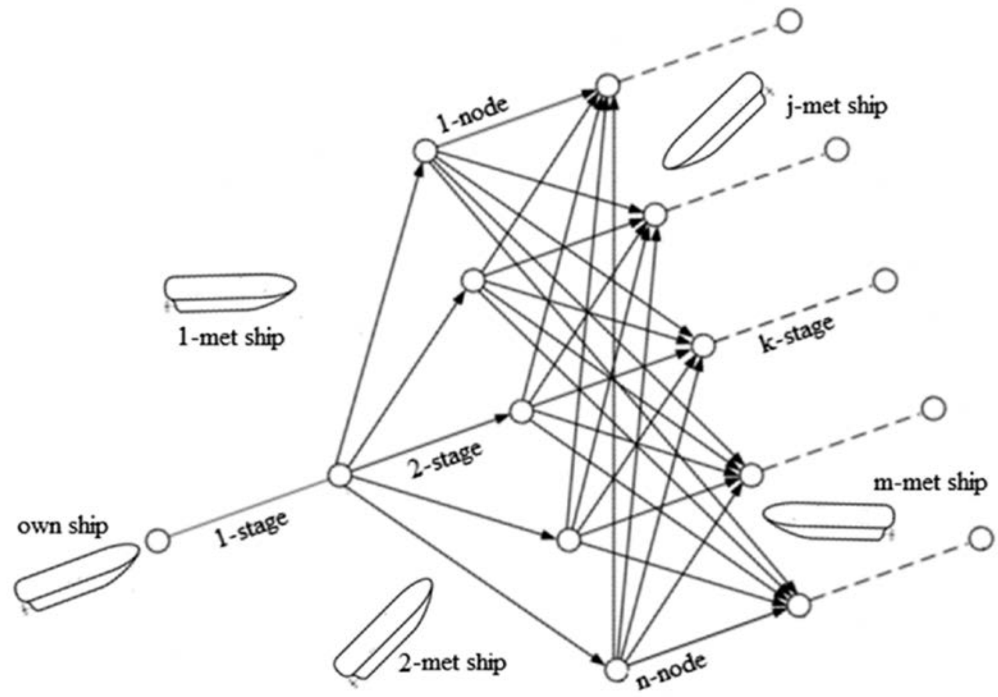

Figure 4. Determination of the ship's safe and optimal trajectory by means dynamic programming method

The optimal time for the ship to go through the *k* stages is a function of the system's state at the end of the *k*–1 stage and control ($u_{1,\,k-2}$, $u_{2,\,k-2}$) at the *k*–2 stage (Figure 4).

By going from the first stage to the last one, formula (15) determines Bellman's functional equation for the process of the ship's control by the alteration of the angle of the rudder angle and the rotational speed of the propeller. The constraints for the state variables and the control values generate the *neural constraints* procedure in the computer algorithm *dynopttraj* for the determination of the safe ship trajectory.

The consideration of the constraints resulting from maintaining a safe approaching distance and the recommendations of the way priority law is performed by checking whether the state variables have not exceeded constraints in form of neural domains in each of the intersections considered and by rejecting the intersections in which the excess has been discovered (Speyer & Jacobson, 2010; Guenin, Konemann & Tuncel, 2014).

Computer simulation

The trajectories have been computed by means of the *dynopttraj* programme for the ship's situations recorded in the Kattegat Strait, both for conditions of good and restricted visibility at sea (Figures 5–7).

Conclusions

The synthesis of safe and optimal control of the ship improves the problem of steering using the dynamic programming method with a relatively precise description of the dynamic properties.

The synthesis of the steering process described in this paper (concluding with a description of appropriate algorithms for determining the optimal control procedures) forms a basis for the development of a computer program for the definition of the safe trajectory of a ship with the use of information from the on-board anti-collision system.

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

The neural networks presented in this paper may be used as elements of the systems for the assessment of the safety of the ships passing by the introduction of the possibility to make a current correction of the sizes of ships' domains. They are able to represent the heuristic knowledge in a similar way to an experienced navigator.

The correctness of the assessment of the safety of the passing vessels with the use of the networks depends, to a decisive degree, on the correctness of

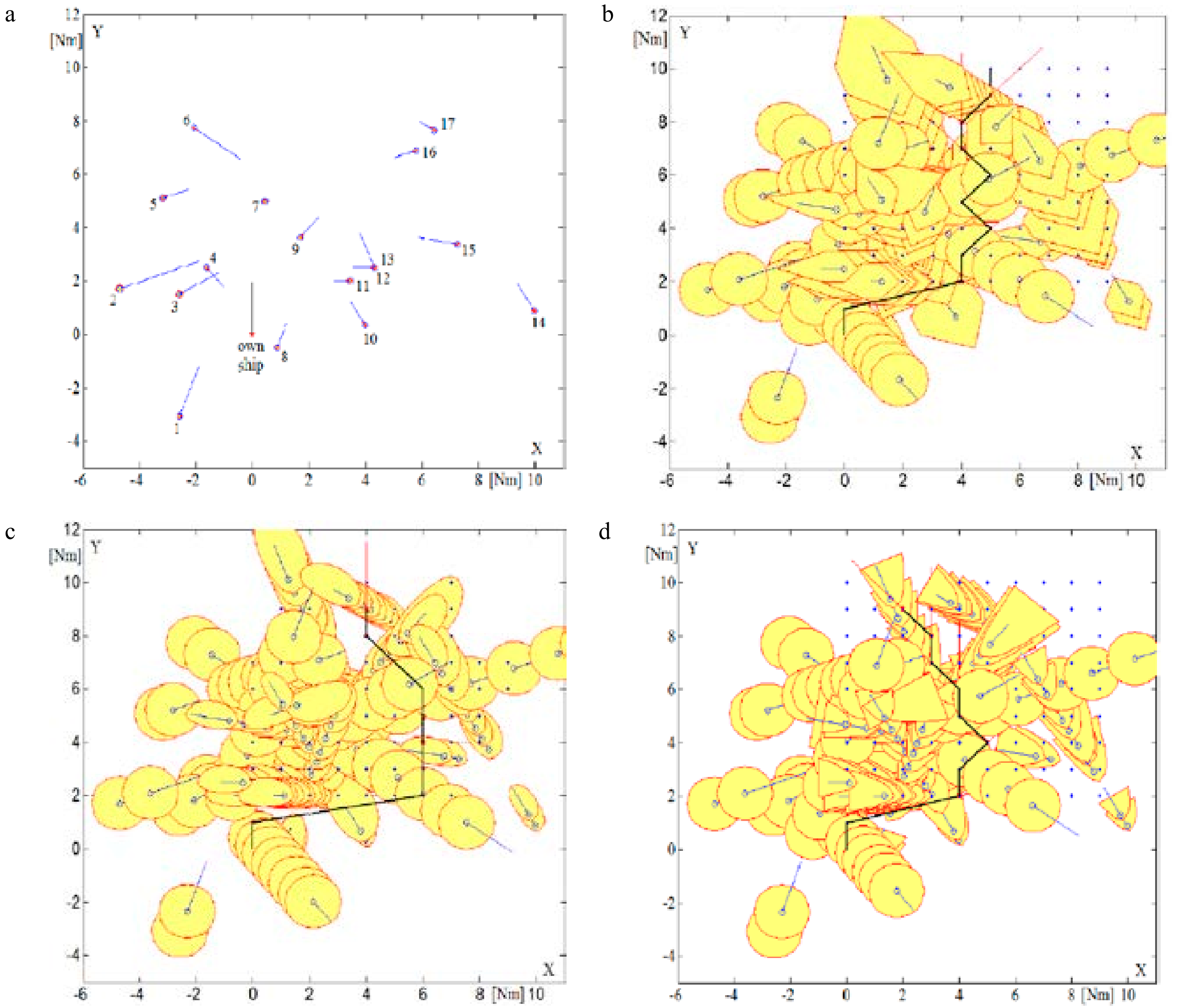

Figure 5. Comparison of safe ship trajectories for different domain shapes in case of 17 met ships and good visibility at sea, D_s = 1.0 nm: a – 12 minutes velocity vectors of ships, b – circle and hexagonal domains t_k^* = 4211 s, c – circle and elliptic domains t_k^* = 4798 s, d – circle and parabolic domains t_k^* = 4093 s

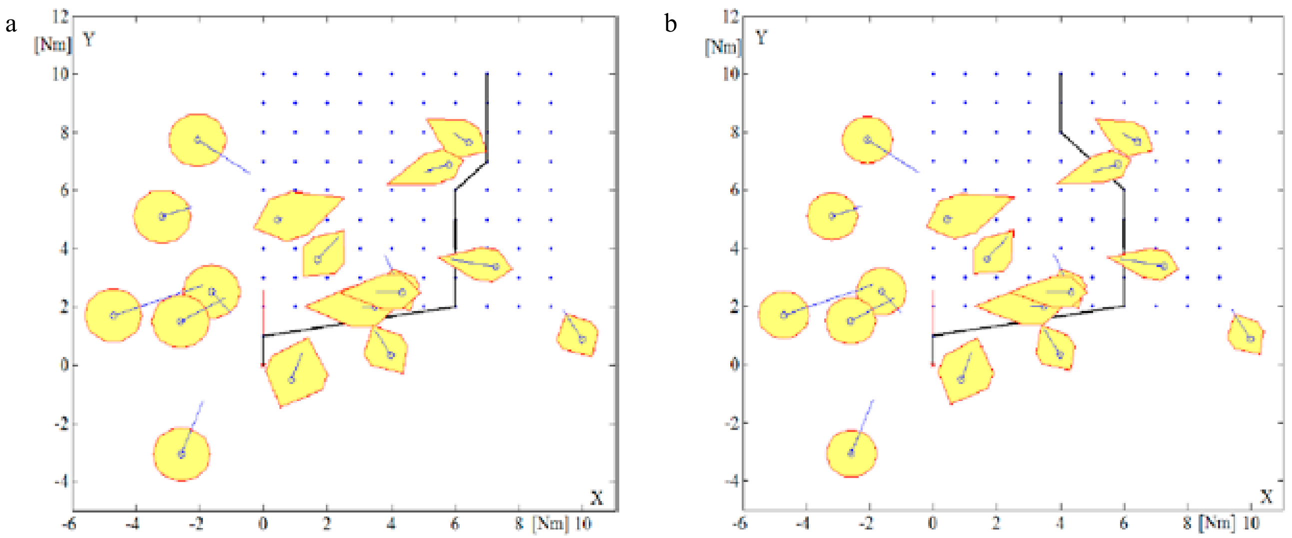

Figure 6. Computer simulation results of the safe ship trajectory in case of 17 encountered ships and good visibility at sea with circle and hexagonal domains: a – D_s = 0.9 nm t_k^* = 4384 s, b – D_s = 0.8 nm t_k^* = 4499 s

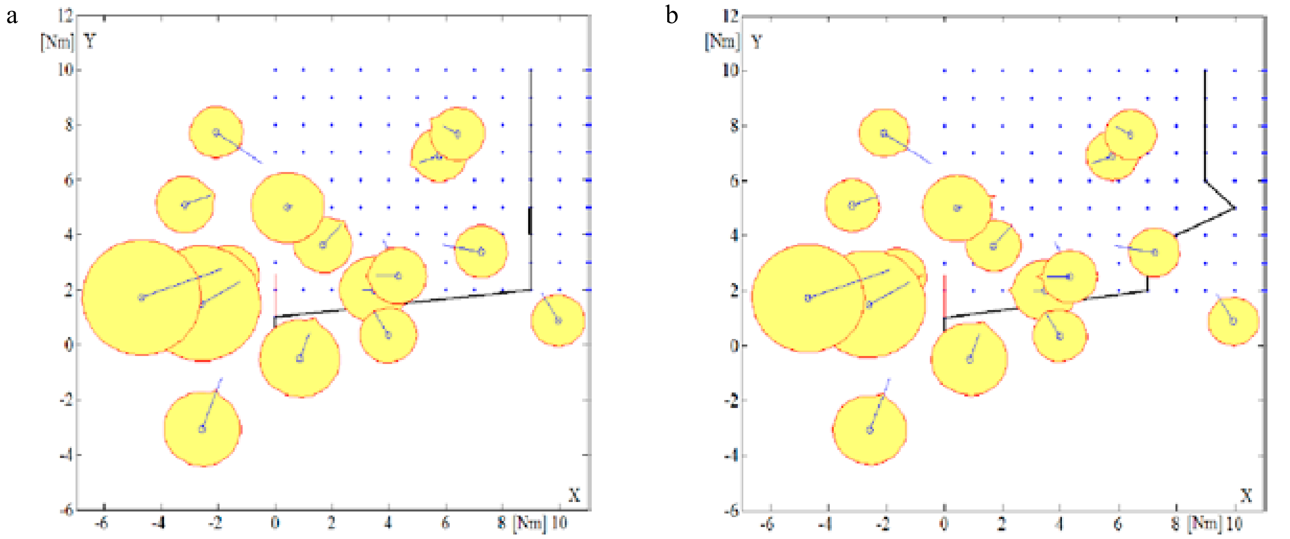

Figure 7. Computer simulation results of the safe ship trajectory in case of 17 encountered ships and restricted visibility at sea with circle domains: a – D_s = 1.5 nm t_k^* = 5092 s, b – D_s = 1.4 nm t_k^* = 5022 s

the data used in the process of the learning network. The use of the knowledge of a few experienced navigators during the learning by the network may lead to the situation in which the network acquires their averaged knowledge.

The introduction of elements of the computational intelligence, represented by a properly prepared network, to determine the ship's domain and, as a consequence, safe trajectory in a collision situation, may help less experienced navigators in the supervision of the anti-collision system assisting the navigational situation, increase the safety of the anti-collision manoeuvre and accelerate the process of selecting a manoeuvre to avoid the collision.

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References

1. Bellman, R.E. (1957) *Dynamic programming*. New York: Princeton University Press.
2. Bist, D.S. (2000) *Safety and security at sea*. Oxford-New Delhi: Butter Heinemann.
3. Colley, B.A., Curtis, R.G. & Stockel, C.T. (1983) Manoeuvring times, domains and arenas. *Journal of Navigation* 36. pp. 324–328.
4. Cross, S.J. (1994) *Objective assessment of maritime simulator training*. Proc. of the Int. Conf. the Development and Implementation of International Maritime Training Standards, Malmo.
5. Davie, P.V., Dove, M.J. & Stockel, C.T. (1980) A computer simulation of marine traffic using domains and arenas. *Journal of Navigation* 33. pp. 215–222.
6. Goodvin, E.M. (1975) A statistical study of ship domains. *Journal of Navigation* 28. pp. 328–334.
7. Guenin, B., Konemann, J. & Tuncel, L. (2014) *A gentle introduction to optimization*. United Kingdom, Cambridge University Press.
8. Hertz, J., Krogh, A. & Palmer, R.G. (1991) *Introduction to the theory of neural computation*. Addison-Wesley Publ.
9. Hunt, K.J., Irwin, G.R. & Warwick, K. (1995) *Neural network engineering in dynamic control systems.Advances in industrial control series*. Springer.
10. Kouemou, G. (2009) *Radar technology*. Chapter 4 by Józef Lisowski: Sensitivity of safe game ship control on base information from ARPA radar, Croatia, In-tech, pp. 61–86.
11. Leondes, C.T. (1998) *Control and dynamic systems, neural network systems techniques and applications*. Vol. 7. Academic Press.
12. Lew, A. & Mauch, H. (2007) *Dynamic programming – a computational tool*. Springer
13. Modarres, M. (2006) *Risk analysis in engineering*. Boca Raton: Taylor & Francis Group.
14. Speyer, J.L. & Jacobson, D.H. (2010) *Primer on optimal control theory*. Toronto: SIAM.
15. Wiśniewski, B. (2011) Integrated problem of ship route planning. Silesian University of Technology, *Archives of Transport System Telematic* 4, 4. pp. 58–64.