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Improved Adaptive Neural Network Autopilot for Track-keeping Control of Ships: Design and Simulation

Phung-Hung Nguyen · Yun-Chul Jung***

* *Graduate school, Korea Maritime University, Pusan 606-791, Korea*
** *Professor, Div. of Navigation Systems Engineering, Korea Maritime University, Pusan 606-791, Korea*

Abstract : *This paper presents an improved adaptive neural network autopilot based on our previous study for track-keeping control of ships. The proposed optimal neural network controller can automatically adapt its learning rate and number of iterations. Firstly, the track-keeping control system of ships is described. For the track-keeping control task, a way-point based guidance system is applied. To improve the track-keeping ability, the off-track distance caused by external disturbances is considered in learning process of neural network controller. The simulations of track-keeping performance are presented under the influence of sea current and wind as well as measurement noise. The toolbox for track-keeping simulation on Mercator chart is also introduced.*

Key words : *Adaptive neural network, Autopilot, Track-keeping, Ship control, Track-keeping simulation.*

1. Introduction

In our previous studies (Nguyen and Jung, 2005; Nguyen and Jung, 2006) an autopilot using adaptive neural network by adaptive interaction (hereinafter called ANNAI autopilot), whose parameters can automatically be adapted, was proposed for course-keeping and track-keeping control. The ANNAI autopilot combined with Line-of-Sight (LOS) guidance algorithm (Fossen, 2002) showed good performance without the influence of sea current acting on ship. In addition external disturbances, especially sea current, make the ship deviate from the intended track. To improve the performance of track-keeping control, the lateral off-track distance from the intended track will be considered.

The improvement of the ANNAI autopilot for track-keeping is conducted by considering the lateral off-track distance from the intended track in the learning process of neural network controller (hereinafter called NNC). In this paper a new solution for the above problem is proposed for track-keeping control by combining the modified LOS guidance algorithm with an improved ANNAI autopilot. Thus both the advantage of LOS guidance algorithm and the adaptability of the ANNAI autopilot are exploited. Using this solution the control problem becomes SIMO (Single Input-Multi Output) control similar in Zhang *et al.*(1997), in which the rudder is used to minimize both the lateral off-track distance and the heading error.

For simulating the track-keeping performance, a mathematical ship model is used. MATLAB modules built for guidance system and displaying the movement of ship on Mercator projection chart are proposed. For visually displaying, M-Maps toolbox (Rich, 2005) for MATLAB is applied.

2. The Design of an Improved ANNAI Autopilot for Track-keeping

2.1 The ANNAI Autopilot for Track-keeping Control

In this subchapter the ANNAI autopilot for track-keeping control proposed in Nguyen and Jung(2005) is reviewed, and an improved ANNAI autopilot is introduced in the next subchapter.

The NNC is a multilayer feedforward neural network with one hidden layer. The configuration of the NNC is shown in Fig. 1, where w_{ij} is used to indicate the weights between output layer and hidden layer, w_{jp} is used to indicate the weights between hidden layer and input layer. The subscripts *p, i*, and *j* indicate the number of neurons in input, output and hidden layer respectively. The input signals of the NNC are merely heading error and its time-delayed values. ψ_k^d and ψ_k are desired heading and actual heading respectively. The neurons in hidden layer have sigmoidal activation function.

The ANNAI autopilot has the adaptation law for the

* Corresponding Author : Phung-Hung Nguyen, hungdktb@hotmail.com, 051)410-4286
** ycjung@hhu.ac.kr, 051)410-4286

hidden layer weights and output layer weights as described in the following equations respectively.

$$\dot{w_{jp}} = O_p[\phi_j\sigma(-I_j)+\gamma.0] = O_p\phi_j\sigma(-I_j) \quad (1)$$

$$\begin{aligned}\dot{w_{ij}} &= \gamma\sigma(I_j).(\rho e_k+\lambda\delta_k+\sigma r_k)\\ &= \gamma.O_j.(\rho e_k+\lambda\delta_k+\sigma r_k)\end{aligned} \quad (2)$$

where,

$$\phi_j = w_{ij}.\dot{w_{ij}} \quad (3)$$

$$\sigma(I_j) = \frac{1}{1+exp(-I_j)} \quad (4)$$

The following cost function as in Zhang *et al.*(1997) is used

$$E_k = \frac{1}{2}[\rho(\psi_k^d-\psi_k)^2+\lambda\delta_k^2+\sigma r_k^2] \quad (5)$$

For reference, the detailed explanation of Eqs.(1)~(5) was already given in Nguyen and Jung(2005).

The above ANNAI autopilot is combined with a LOS guidance algorithm to perform track-keeping control task. The intended track consists of waypoints and the straight lines connecting the waypoints from departure to arrival. LOS guidance was presented in Fossen(2002) and applied to surface ships in previous works such as Vukic *et al.*(1997), Nguyen and Jung(2005).

The configuration of the ANNAI track-keeping controller is shown in Fig. 1. The LOS guidance system produces guidance heading signals for ship to follow and make the ship position converge to the predefined track.

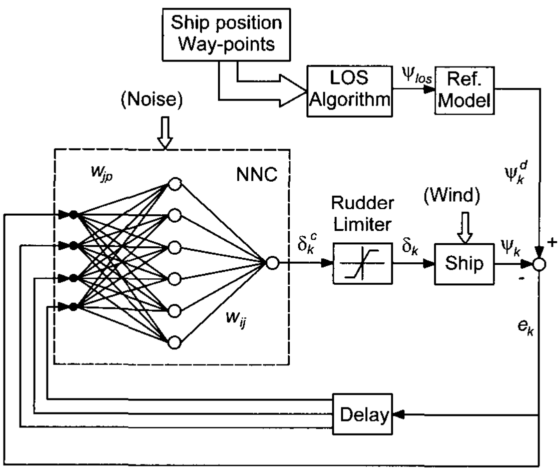

Fig. 1 Track-keeping control system using ANNAI autopilot and LOS guidance algorithm

2.2 An Improved ANNAI Autopilot Design for Track-keeping Control

1) Effect of Disturbances on Ship's Track

In navigational practice, precise track-keeping performance of a ship is always affected by external disturbances such as sea current and wind. If those effects are considerable then the accurate track-keeping of ship is deteriorated, especially in the case of navigation in restricted waters. In such situations the conventional LOS guidance algorithm can not help to perform good track-keeping ability (Vukic, 1997).

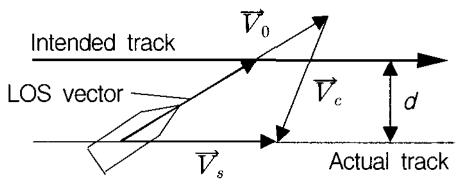

Fig. 2 Track-keeping using LOS guidance under influence of sea current

Fig. 2 shows LOS guidance algorithm performance for track-keeping under the influence of sea current. If the following equality holds

$$\vec{V}_s = \vec{V}_0 + \vec{V}_c \quad (6)$$

where $\vec{V}_s$, $\vec{V}_0$, and $\vec{V}_c$ are ship's actual speed, speed of advance and current speed, respectively, and $\vec{V}_0$ has same direction with LOS vector, then actual track of the ship is clear off the intended track a certain distance *d*.

2) Improved ANNAI Autopilot Design

In 1997, Zhang *et al.* introduced a SIMO adaptive NNC for track-keeping using backpropagation training method. The rudder is used to minimize both the lateral off-track distance and the heading error which is tangent with desired path.

Later, Velagic *et al.*(2003) presented an adaptive fuzzy autopilot for track-keeping. In their study, the lateral off-track distance was used as an input to *"Adjustable scaling factor mechanism"* which provided the fuzzy autopilot the adaptability with external disturbances.

Zhuo and Hearn(2004) introduced an intelligent track-keeping system for ship with specialized learning using neurofuzzy as SIMO controller.

In this paper the off-track distance is considered to design a SIMO track-keeping control system based on the

ANNAI autopilot developed in Nguyen and Jung(2005). The output of the NNC (rudder command) is calculated to minimize both the lateral off-track distance and the error between actual ship heading and LOS guidance signal.

The LOS guidance signal (ψ_{LOS}) is calculated by LOSMERCATOR module (see subchapter 3.1) which is described in Fig. 3. Let $A(l_{k-1}, L_{k-1})$, $B(l_k, L_k)$ be previous and current waypoints positions in latitude and longitude respectively. N is intersection point of LOS vector and AB. The middle latitude (see Yoon and Jeon, 2005) as follows in Eq.(7)

$$l_m = \frac{1}{2}(l_{k-1} + l_k) \tag{7}$$

In Fig. 3, S(l_{ship}, L_{ship}) is the ship position and

$$SN = nL, \tag{8}$$

where n is number of ship length L.

$$AC = BD = \Delta l = l_k - l_{k-1} \tag{9}$$

$$AD = BC = \Delta L = (L_k - L_{k-1}) cos l_m \tag{10}$$

$$AG = l_{ship} - l_{k-1} \tag{11}$$

$$AH = (L_{ship} - L_{k-1}) cos l_m \tag{12}$$

Using MECATOR or MIDLAT module introduced later in subchapter 3.1, we can determine the course Co from A to B and distance AB. Similar in Fossen(2002), NF and NE can now be determined. Position of N in latitude and longitude can be calculated as

$$l_{LOS} = l_{k-1} + NF \tag{13}$$

$$L_{LOS} = L_{k-1} + AF/cos l_m \tag{14}$$

From S(l_{ship}, L_{ship}), N(l_{LOS}, L_{LOS}), and using MECATOR or MIDLAT module, we can calculate ψ_{LOS}.

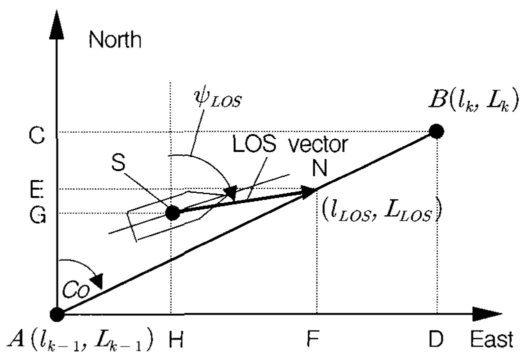

Fig. 3 Calculation of LOS guidance signal

In the LOS algorithm, *wheel over point* (WOP) is the point at which the ship leaves the straight line and enters the circle arc and vice versa. To determine the WOP Fossen(2002) introduced fixed value of the radius of circle of acceptance R_0 in the LOS algorithm. In Vukic *et al.*(1997), R_0 is calculated using table look up method where the value of R_0 at each course changing situation is obtained from ship model testing. Alternatively, in this study R_0 is determined as the distance from waypoint to WOP plus *Reach* (ζ) as expressed in Eq.(15) and shown in Fig. 4 (see Yoon and Jeon, 2005). Value of ζ depends on the condition of ship and the rudder angle.

$$R_0 = XY = 5\theta + \zeta \tag{15}$$

Equation (15) is included in simulation program for automatic calculation of R_0.

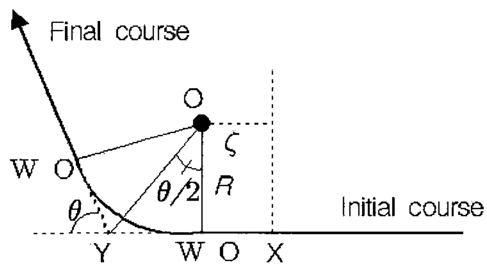

Fig. 4 *Wheel-Over-Point* and *Reach* while changing course

The configuration of the track-keeping control system is shown in Fig. 5, and the cost function is modified. Using the method introduced in Vukic *et al.*(1998), we can determine the off-track distance d and its sign. We also define normalized off-track distance as $\eta = d/L$, where L is the length of ship. The cost function in Eq.(5) is modified as follows

$$E_k = \frac{1}{2}[\rho_1(\psi_k^d - \psi_k)^2 + \rho_2(\eta_k^d - \eta_k)^2 + \lambda\delta_k^2 + \sigma r_k^2] \tag{16}$$

Similar in Nguyen and Jung(2005), it is possible to write

$$\frac{\partial E_k}{\partial \psi_k} = \frac{\partial E_k}{\partial \psi_k} - \frac{\partial E_k}{\partial \delta_k} + 2\frac{\partial E_k}{\partial r_k}\frac{\partial r_k}{\partial \delta_k} - \frac{\partial E_k}{\partial \eta_k}\frac{\partial \eta_k}{\partial \delta_k} \tag{17}$$

From Eq.(17), by replacing $\partial r_k/\partial \delta_k$ and $\partial \eta_k/\partial \delta_k$ with $\partial r_k/\partial \delta_k = -1$ and $\partial \eta_k/\partial \delta_k = -1$ respectively, one can obtain

$$\frac{\partial E_k}{\partial \psi_k} = -\rho_1(\psi_k^d - \psi_k) - \rho_2(\eta_k^d - \eta_k) sign(\frac{\partial \eta_k}{\partial \delta_k}) - \lambda\delta_k + 2\sigma r_k sign(\frac{\partial r_k}{\partial \delta_k}) \tag{18}$$

$$\frac{\partial E_k}{\partial \psi_k} = -[\rho_1(\psi_k^d - \psi_k) - \rho_2(\eta_k^d - \eta_k) + \lambda\delta_k + 2\sigma r_k] \quad (19)$$

Note that the desired value $\eta_k^d = 0$, so Eq.(2) can be modified as

$$\begin{aligned} \dot{w}_{ij} &= \gamma.\sigma(I_j).(\rho_1 e_k + \rho_2 \eta_k + \lambda\delta_k + \sigma r_k) \\ &= \gamma.O_j.(\rho_1 e_k + \rho_2 \eta_k + \lambda\delta_k + \sigma r_k) \end{aligned} \quad (20)$$

Depending on the value η_k, we select ρ_2 as follows

$$\rho_2 = \alpha + \beta.\ |\ \eta_k\ | \quad (21)$$

where α and β are positive constants. Equation (21) can improve the adaptability of the autopilot since the ANNAI is more sensitive to the off-track distance.

To summarize, the improved ANNAI autopilot has the adaptation law for the hidden layer weights and output layer weights as described in Eqs.(1) and (20) respectively. Based on the above improved ANNAI autopilot, we propose a track-keeping control system shown in Fig. 5.

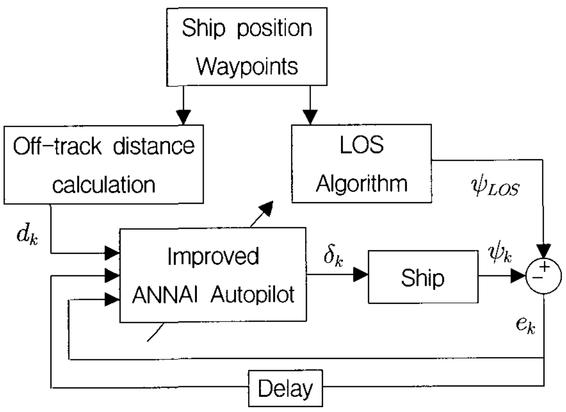

Fig. 5 Configuration of the track-keeping control system using the improved ANNAI autopilot

3. Simulation

3.1 Simulation Tools

1) Modules for Guidance Using MATLAB

In this study the modules written in MATLAB are introduced for guidance and control using Mercator chart. They can be used to calculate and display ship's movement on the navigational equipment monitors. The followings are brief descriptionsof the module programs:

LOSMERCATOR calculates LOS guidance signal using Mercator formula (Yoon and Jeon, 2005).

MERCATOR calculates distance and course between two points on Mercator chart using Mercator formula.

MIDLAT calculates distance and course between two points on Mercator chart using middle-latitude formula (Yoon and Jeon, 2005).

NEXTPOS calculates next position from one position if distance and course between the two positions are known. This calculation is based on middle latitude method.

OFFTRACKDIST calculates off-track distance from ship position to desired track in way-point navigation.

SHIPICON returns vector of points for drawing ship icon on Mercator chart for moving animation of ship motion. It can use real dimensions of ship.

WOP returns distance from current way-point to the respective Wheel-Over-Point at which ship turns to new course.

2) M-Maps Toolbox for MATLAB

M-Maps Toolbox, which is a set of mapping tools written in MATLAB and was available in Rich(2005), is used for visual simulation of ship's movement. Fig. 6 shows an example of simulation of a ship departing from Pusan bay using M-Maps Toolbox and module programs in subchapter 3.1.

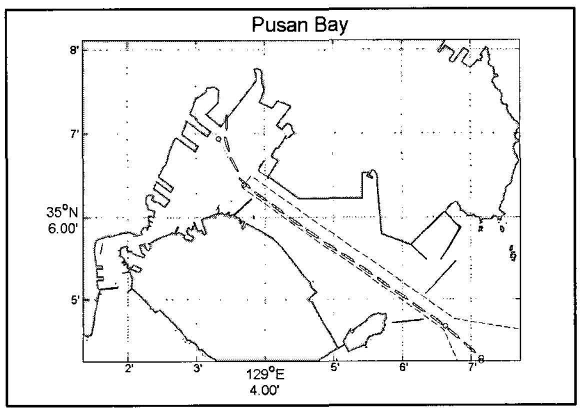

Fig. 6 Simulation of a ship departing from Pusan bay

3) Ship Model

In this paper the mathematical ship model is used for simulating and testing the performance of the controller. The simulations are carried out for a Mariner Class Vessel, the nonlinear model of which can be found in GNC Toolbox for MATLAB (Fossen, 2005). The planar motion mechanism tests and full-scale steering and maneuvering predictions for this Mariner Class Vessel were performed by the hydro-aerodynamics laboratory in Lyngby, Denmark.

4) External Disturbances and Measurement Noise

Among many possible external disturbances acting on a ship only two will be applied here. They are sea current and wind, which mainly influence the track-keeping performance.

To simulate sea current, the two-dimensional current model Fossen(2002) is used here. Sea current true direction of 220^0 and velocity varying from 0.5 to 1 m/s is used.

The effect of wind disturbance against the body of ship is based on the work of Isherwood(1972) introduced in Fossen(2002) with wind speed changes randomly from 10 knots to 20 knots every 5 seconds, wind direction changes randomly from 0^0 to 90^0 every 30 seconds.

A random signal with a uniform distribution on [-0.1^0, $+0.1^0$] is used as the sensor noise in the heading sensor.

3.2 Track-keeping Simulation Results

In this subchapter, simulation results of the ANNAI autopilot and the improved ANNAI autopilot are presented to show the improvement of the later. Firstly, performance of the previously developed ANNAI autopilot for track-keeping introduced in 2.1 is simulated. Finally, simulation of the improved ANNAI autopilot in 2.2 for the same task will be shown.

In this study, we select the NNC with p = 4, i = 1, and j = 6. The input neurons have linear activation functions, the hidden neurons have sigmoidal activation function and the output one has tangent sigmoidal activation function. The following parameters are used.

$$[\rho_1, \lambda, \sigma, \alpha, \beta] = [1.0, 0.2, 0.2, 0.4, 0.6] \quad (22)$$

The intended track consists of four waypoints (34.8333^{0}N, 128.8333^{0}E), (34.857^{0}N, 128.8333^{0}E), (34.857^{0}N, 128.8873^{0}E), (34.8333^{0}N, 128.8873^{0}E). The initial ship position and heading are (34.8333^{0}N, 128.83153^{0}E) and 020^0. For each simulation only the plotting of ship position is shown here. The ship position on the track is plotted every 120 seconds. Other recorded data is attached in Appendix.

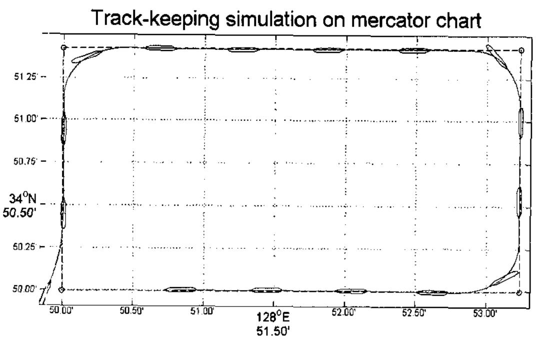

Fig. 7 Track-keeping control of the *ANNAI autopilot* without the influence of disturbances

In Fig. 7 and Fig. 8, track-keeping control simulations of the ANNAI autopilot without and with the influence of disturbances are shown, respectively. The intended track is dashed line and the actual track is solid one.

Without external disturbances the ship is nicely kept along the intended track Fig. 7. However, being affected by disturbances the ship is about a certain distance d clear off the track Fig. 8.

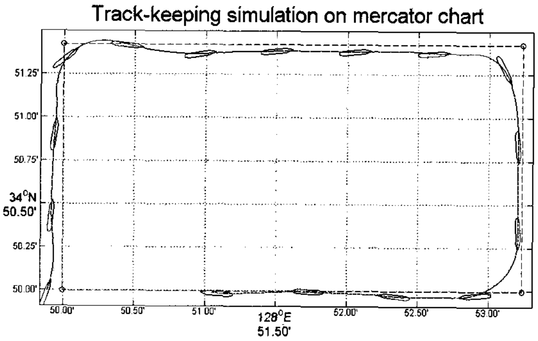

Fig. 8 Track-keeping control of the *ANNAI autopilot* with the influence of disturbances

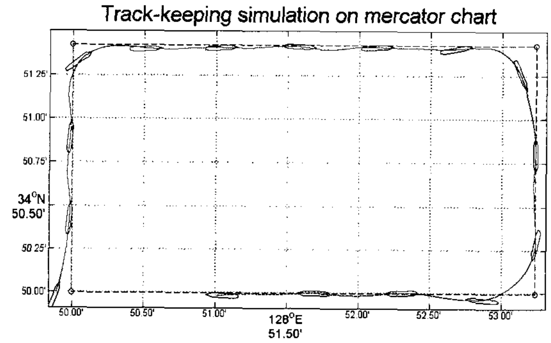

Fig. 9 Track-keeping control of the *improved ANNAI autopilot* with the influence of disturbances

In Fig. 9, the simulation of track-keeping performance using the improved ANNAI autopilot with LOS guidance algorithm is shown. Although under the influence of the external disturbances, the ship can converge fast to new course and keep close to the intended track, the off-track distance is much reduced in comparison with that in Fig. 8. From the case in Fig. 9, it is also observed that the rudder responded actively due to the effects of the external disturbances (see more at Appendix).

4. Conclusion

In this study, an improved ANNAI autopilot is developed for track-keeping control of ship. LOS guidance algorithm is applied to calculate guidance course for the autopilot. The proposed method has shown good performance under the influence of external disturbances.

Principally, the differences between the proposed adaptive track-keeping control scheme and the ones proposed in previous studies are

- The method to calculate guidance signal and radius of circle of acceptance R_0 in the LOS algorithm.
- The use of normalized off-track distance in learning process of the ANNAI.
- The combination of the improved ANNAI autopilot with modified LOS algorithm.

For simulation purpose, module programs written in MATLAB are introduced for guidance and control using Mercator chart. They can be used to calculate and display ship's movement on the navigational equipment monitors such as ECDIS (Electronic Chart Display and Information System). M-Maps toolbox for MATLAB is applied for visually displaying ship's movement.

Our purpose is to improve the ANNAI autopilot for track-keeping employing the learning ability of the NNC. The improved ANNAI autopilot must have adaptability with external effects. This purpose has been achieved.

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Appendixes

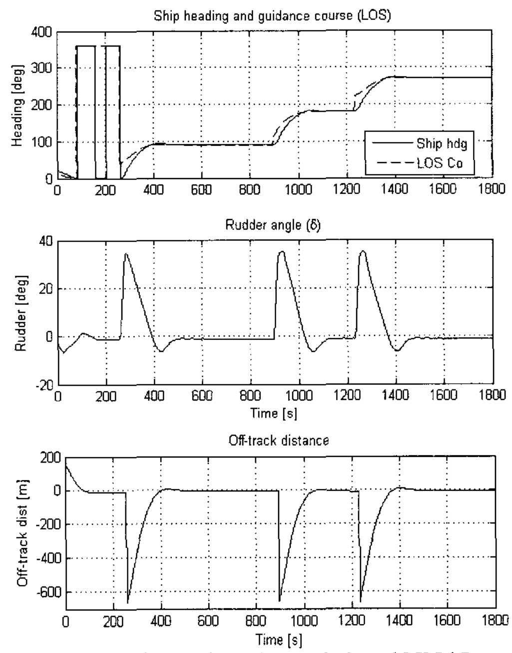

Fig. 10 Recorded simulation data of the *ANNAI autopilot* without the influence of disturbances in Fig. 7

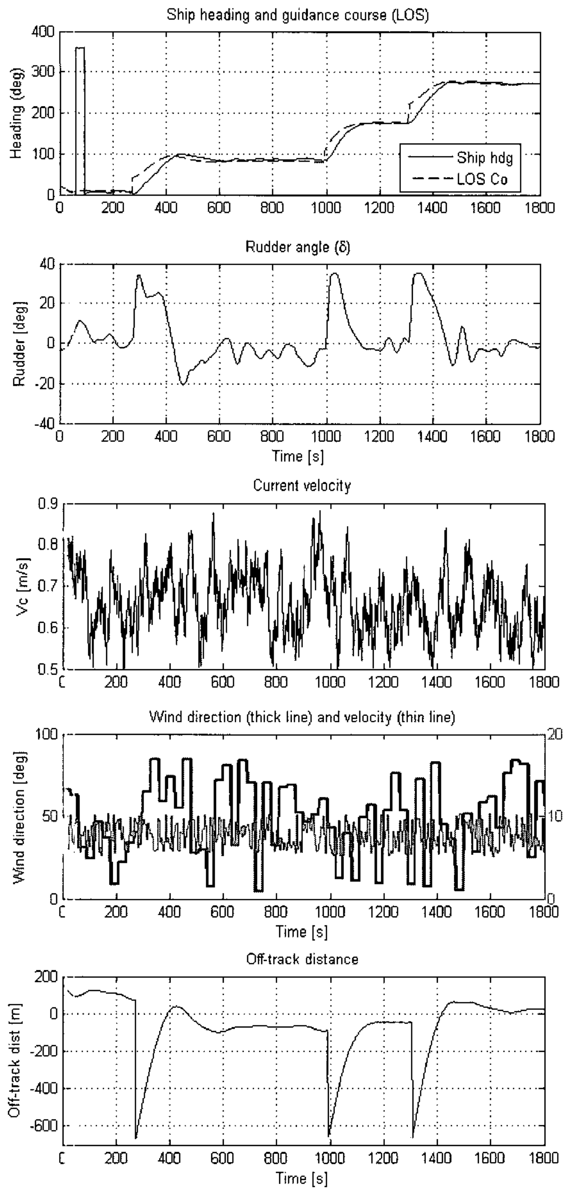

Fig. 11 Recorded simulation data of the *ANNAI autopilot* with the influence of disturbances in Fig. 8

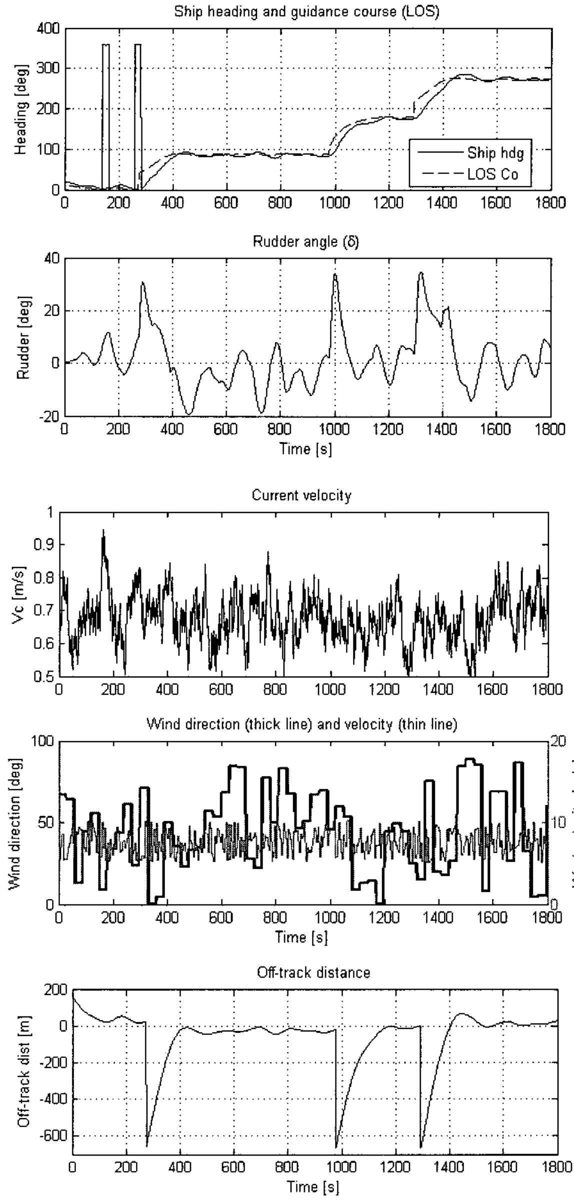

Fig. 12 Recorded simulation data of the *improved ANNAI autopilot* with the influence of disturbances in Fig. 9

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