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Formation control of marine vehicles during replenishment operations

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Abstract. Formation control consists in stabilising distances between ships during their motion at the same speed. Due to necessary coordination of motion of the ships, a structure is composed which allows constant distance to be kept between the ships with an assumed accuracy. Formation control makes use of the Leader-Follower algorithm. The steering structure includes the superior formation controller and real-time trajectory controllers. Direct course and speed steering is executed using PD fuzzy controllers. The application of advanced technologies provides opportunities for reducing the number of crew involved in at-sea reloading activities and increasing ship safety during operations of this type.

Keywords. Formation control, Leader – Follower algorithm, fuzzy controller

1 Introduction

Ship reloading operations performed at sea aim at prolonging the time of ship's stay at sea, which is limited by the volume of shipped fuel and food reserves [4],[9]. The first successful operation of this type took place in 1899. USS Marcellus completed coal reserves on the battle ship USS Massachusetts. Since then, numerous methods of reloading the reserves at sea have been developed. At present, reloading operations at sea can be divided into two groups: connected replenishment and vertical replenishment. In the connected replenishment ships are linked together by a system of hoses. Most often the ships move in a parallel formation, at a small distance from each other. Another sometimes observed formation is that two ships sail one after the other. The vertical replenishment takes place with the assistance of a helicopter.

For the time being, optical methods have not been used in systems for automatic ship formation control. However, laser range-finders were successfully used for these purposes the role of which was to measure manually the distance between ships during the operation of at-sea reloading [9]. The investigations have confirmed high efficiency of use of the range-finders in those operations and their extremely high accuracy, as a result of which they were recommended for use in US Navy.

In order to secure safe reloading between ships at sea, a Leader-Follower algorithm was developed [1],[8], which makes use of a fuzzy course and speed controller for ship steering. The formation consists of two ships:

1. The main ship leading the entire formation – the Leader.
2. The ship that follows the movements of the main ship, and mainly aims at keeping the formation – the Follower.

The ships move along precisely defined passing trajectories, at a constant distance between each other. Direct steering of engine rotational speed and rudder deflections are executed by fuzzy PD controllers. The trajectory controller makes use of a virtual ship as a reference object, a concept which was earlier used for steering a single ship along an assumed trajectory [6],[7].

2 Formation controller

Formation control can be reduced to the task of synchronisation of ship motion along assumed trajectories, certain distances between the ships being preserved by specialised distance measuring instruments to secure safe motion of the ships [3]. The formation control makes use of a modified Leader-Follower algorithm.

The ship which leads the formation is the Leader. It selects the trajectory along which the entire formation moves. In individual cases, manual steering of the Leader is possible. The Follower moves at Leader's side. Its task is to follow Leader's movements in such a way that the two ships keep a constant distance between each other and their positions in the formation as a whole.

The Leader moves along the earlier assumed trajectory. The trajectory for the Follower is parallelly displaced with respect to that of the Leader, in such a way that the condition of keeping the earlier assumed constant distance between the two vessels is met.

The formation control algorithm consists of three phases:

- Phase 1: Synchronisation of ship motion. In this phase, ships which have been moving independently compose a common parallel formation moving at a certain speed. The Follower modifies its motion to take position at a certain distance beside the Leader.
- Phase 2: Moving within the formation. In this phase the ships move within the earlier created formation. The distance between the ships is determined precisely using laser range-finders Disto Pro4a made by Leica. Distances between ships' boards at bow and stern are measured, and additionally in the middle of each ship (Fig. 2.1).
- Phase 3: Changing formation. Changing distances between the ships in the formation is possible, in both increasing and decreasing direction. The Leader's trajectory remains unchanged, while the Follower changes its position in the formation. Once the manoeuvre has been completed, the ships return to phase 2.

An important problem during the motion of ships composing a formation is exchange of information between the ships in order to steer safely the entire formation. In Phase 1 and Phase 3 the Leader passes the information on its position and speed to the Follower. In Phase 2 the information on relative positions of the ships comes from Follower's measuring systems. The Leader only sends messages on its speed. This configuration secures the minimum of the passed data. In case of any failure in contact between the ships, the distance between them is continuously measured to allow safely the emergency termination of the motion in formation to be completed, which their further motion at a safe distance. An additional argument in favour of the use of range-finders is extremely short time of measurement (up to 1 second) and high accuracy (up to 1,5 mm).

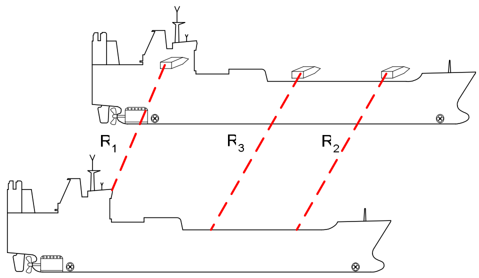

Figure 2.1. Distribution of laser range-finders on ships in the formation

3 Trajectory controller

Figure 3.1 shows a scheme of the control system, which consists of the superior formation controller and two trajectory controllers, which steer the Leader and the Follower. The structure of the trajectory controller is identical for the Leader and the Follower. What is different is the way in which the set values are determined. For the Leader the information about the passed trajectory and current speed is delivered from outside, for instance it can be planned by the navigator. Leader's position and speed are passed to the formation controller, to which the information about Follower's position is passed as well. Based on these data and taking into account the selected shape of ship's formation the formation controller works out the information about the trajectory and passes it to the Follower's trajectory controller.

The developed trajectory controller [6],[7] (Fig. 3.1) consists of two controllers working in parallel: the course controller and the speed controller. These controllers were designed making use of the fuzzy set theory. Their task is to minimise corresponding course errors e_Ψ (difference between the set and real course) and speed errors e_V (difference between the set and real speed).

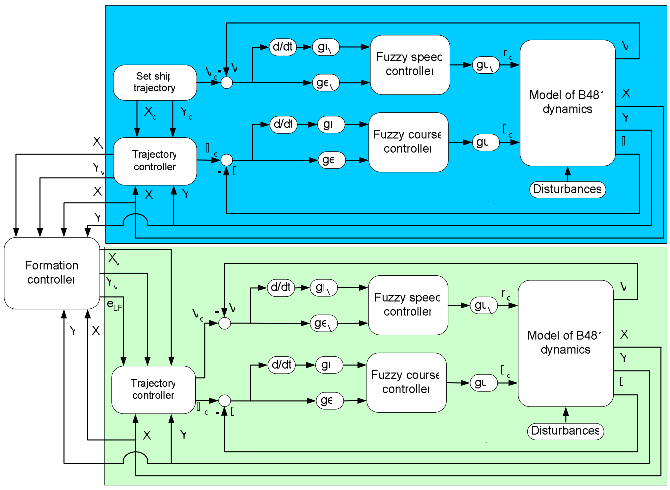

Figure 3.1. Block diagram of the control system

The input variables for the course controller are the course error e_ψ and its derivative r_ψ. (r_ψ.=de_ψ/dt). The output signal is the rudder deflection to be passed to the steering engine δ_c. Figure 3.2 shows the shape of the membership function for the fuzzy course controller.

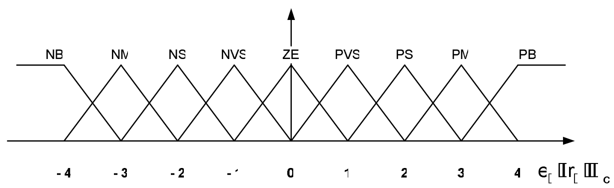

Figure 3.2. Shape of the membership function for the course controller

The input signals were normalised within the range [-4, 4], while the output signals were scaled from the range [-4, 4] to real values using scaling amplifications (ge_ψ, gr_ψ, gu_ψ). For the controlled defined in the above way 81 rules of control are obtained (Table 3.1). For the course controller the following linguistic variables were adopted: NB – negative big, NM – negative medium, NS – negative small, NVS – negative very small, ZE – zero, PSV – positive very small, PS – positive small, PM – positive medium, PB – positive big.

The second controller, working in parallel, is the speed controller. The input variables for the speed controller are speed control error e_V and its derivative r_V (r_V.=de_V/dt). The controller produces the rotational speed n_c of the ship's screw propeller. The shape of the membership function for the speed controller is given in Fig. 3.3. Like for the course controller variables, all speed controller's variables were normalised using scaling amplifications (ge_V, gr_V, gu_V), to meet the range <-3,3>.

Table 3.1. Base of rules for the fuzzy course controller in linguistic notation:
e_ψ - course error, r_ψ - course error derivative

$r_\psi \backslash e_\psi$	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB
NB	NB	NB	NB	NB	NB	NM	NS	NVS	ZE
NM	NB	NB	NB	NB	NM	NS	NVS	ZE	PVS
NS	NB	NB	NB	NM	NS	NVS	ZE	PVS	PS
NVS	NB	NB	NM	NS	NVS	ZE	PVS	PS	PM
ZE	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB
PVS	NM	NS	NVS	ZE	PVS	PS	PM	PB	PB
PS	NS	NVS	ZE	PVS	PS	PM	PB	PB	PB
PM	NVS	ZE	PVS	PS	PM	PB	PB	PB	PB
PB	ZE	PVS	PS	PM	PB	PB	PB	PB	PB

The base of rules for the fuzzy speed controller is given in Table 3.2. It consists of 49 control rules. The input and output variables can take the following linguistic values: NB, NM, NS, ZE, PS, PM, PB.

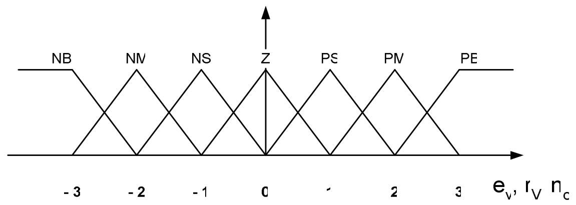

Figure 3.3. Shape of the membership function for the speed controller

Table 3.2. Base of rules for the fuzzy speed controller in linguistic notation:
e_V - speed error, r_V - speed error derivative

$r_V \backslash e_V$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The goal to be obtained by the trajectory controller is to minimise errors E_y and E_x, being, respectively, the lateral and longitudinal deviation of ship's position from the planned trajectory (Fig. 3.4). They can be affected by changing the rudder angle and the main engine rotational speed. During the voyage, as a result of turning manoeuvre or the action of hydro-meteorological disturbances, the real trajectory of the ship motion moves away from the planned one. The course controller working inside the trajectory controller (Fig. 3.4a) minimises the error E_y with respect to the turning point. The ship trajectory error E_y will decrease when the ship nears the set target (at that point the error will be equal to zero). That is why the modification of the course controller consisting in making the error E_y independent on the distance of the own ship from the turning point was necessary. For this purpose a concept of a virtual ship as the reference point was introduced. (Fig. 3.4b). The virtual ship moves exactly along the same trajectory, at a distance R in front of the own ship. Between the turning points the virtual ship moves along straight line segments, while during the turns it moves along circular trajectories. To provide conditions for safe sailing it was assumed that the distance R is constant and is equal to 4L, where L is ship's length.

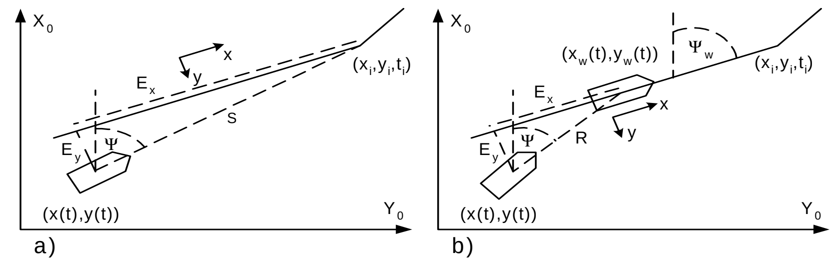

Figure 3.4. Trajectory of a ship steered by the course controller: a) with virtual ship, b) without virtual ship

4 Ship as the object of steering

The operation of the developed trajectory controller was simulated in the closed control system, in which the mathematical model of a container ship bearing the shipyard symbol B-481 was used as a control object.

The model includes the dynamics of the hull and the main propulsion system consisting of a single adjustable blade propeller, rudder, and two lateral thrusters: on the bow and stern sides (Fig. 4.1). The effect of disturbances of environmental origin (wind, waves, sea current) and changes in dynamics caused by shallow water were also taken into account. The model allows analysing the behaviour of the ship for two load conditions: ballast and full load.

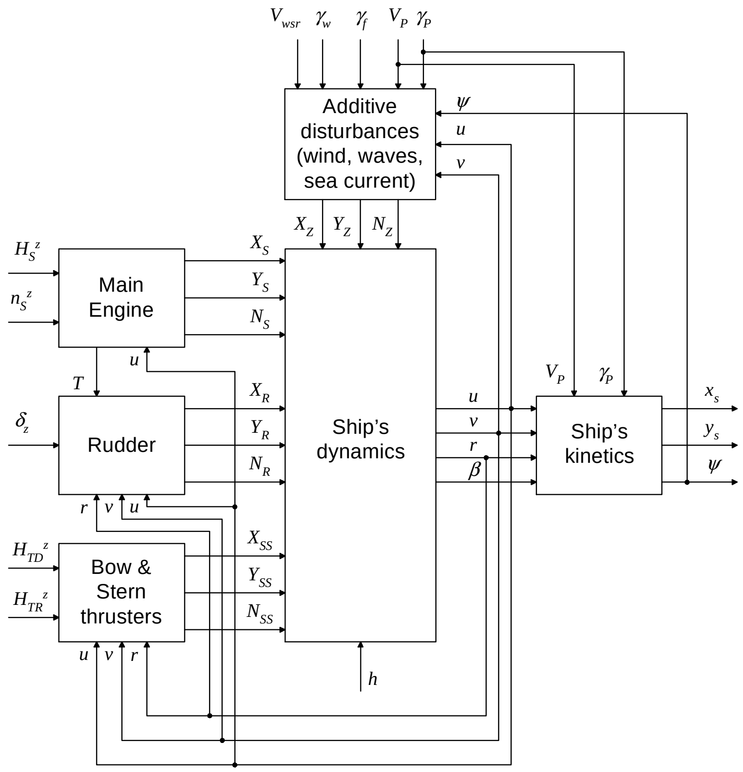

Fig. 4.1. Structure of the mathematical model of the own ship: H^z_S – assumed pitch of the main propulsion adjustable blade propeller, n^z_S – assumed rotations of the main propulsion propeller, T – thrust of the main propulsion propeller, δ_z – assumed deflection of the blade rudder, $H_{TD}{}^z$ – assumed propeller pitch of the bow thruster, $H_{TR}{}^z$ – assumed propeller pitch of the stern thruster, V_{wsr}, γ_w – average speed and direction of the real wind, γ_f – direction of sea waves, V_p, γ_p – speed and direction of sea current, h – depth of the sailing region, u – ship's longitudinal speed, v – ship's transverse speed, r – ship's angular speed, β – drift angle, x_s, y_s – position coordinates, ψ – ship's course, X, Y, N – forces and moments acting on ship's hull [2].

Kinetic relations for determining the position of the ship can be written by the following formula:

$$\begin{aligned} \dot{x}_s &= V\cos(\psi-\beta)+V_p\cos\gamma_p \\ \dot{y}_s &= V\sin(\psi-\beta)+V_p\sin\gamma_p \\ \dot{\psi} &= r \end{aligned} \tag{1}$$

where: V – resultant speed, ψ – course, β – drift angle, r – angular speed, all referring to the own ship.

Then dynamics of the main propulsion is has the following equation:

$$\dot{n}_S = \left(n_S^z - n_S\right)/T_{cn}\ ;\ |n_S|\leq 1 \qquad (2)$$

where: T_{SG}– time constant ; $n^z{}_S$ – assumed propeller rotations.

The equations defining longitudinal, transverse, and angular motion of the own ship take the following form:

$$\begin{aligned}(1+k_{11})\cdot\dot{u} &= X_{tot}\\ (1+k_{22})\cdot\dot{v} &= Y_{tot}\\ (1+k_{66})\cdot\dot{r} &= N_{tot}\end{aligned} \qquad (3)$$

where: u – longitudinal speed, v – transverse speed, r – angular speed; k_{11}, k_{22}, k_{66} – added water mass coefficients taking into account the effect of shallow water, X_{tot}, Y_{tot}, N_{tot} – total forces and moment acting on ship's hull in directions of X, Y and Z axes. These forces are determined from the following relations :

$$\begin{aligned}X_{tot} &= X_K + X_S + X_R + X_{SS} + X_Z\\ Y_{tot} &= Y_K + Y_S + Y_R + Y_{SS} + Y_Z\\ N_{tot} &= N_K + N_S + N_R + N_{SS} + N_Z\end{aligned} \qquad (4)$$

where: X_k, Y_k, N_k – hydrodynamic forces and moment caused by the hull of the own ship and defined by equations (5); X_S, Y_S, N_S – forces and moment from main propulsion, defined by equations (6); X_R, Y_R, N_R – forces and moment from blade rudder, defined by equations. (7); X_{SS}, Y_{SS}, N_{SS} – forces and moment from thrusters, defined by equations (8); X_Z, Y_Z, N_Z – forces and moment from external disturbances, defined by equations (9).

The mathematical model of dynamics of the hull of the own ship is defined by the following relations:

$$\begin{aligned}X_K &= (1+k_{22})vr - \frac{0.075}{2}\cdot\sin\left[\left(\pi - \arcsin\frac{C_{xoh}}{0.075}\right)\left(1-\frac{|\beta|}{\Psi_x}\right)\right]\frac{S_d}{W}V^2\\ Y_K &= -(1+k_{11})ur + \left[\left(\frac{1}{2}c_y^{\beta}\,\hat{a}_1\sin 2\beta\cos\beta + Y_K^t\right)V^2 + a_{41}\left(\frac{T}{h}\right)^2 L_w|r|V\sin\beta\right]\frac{1}{2}\frac{S_d}{W}\\ N_K &= \left[N_K^t - c_{mo}L_w^2 r|r| - C_{mw}\frac{1}{\pi}\left(V^2 + L_w^2 r^2\right)\cdot C_{md}\sin(\pi\cdot\Omega)\right]\frac{\rho}{2}\frac{S_d L_w}{I_z}\end{aligned} \qquad (5)$$

where: C_{xoh} – hull drag coefficient in shallow (deep) water, $\hat{a}_1$– corrections of hydrodynamic coefficients taking into account the effect of shallow water; a_{41}, c^{β}_y, c_{mo}, c_{mwo}, Ψ_x, – hydrodynamic coefficients, constant for given draught; β – drift angle; V – resultant speed of the ship; S_d – calculated surface of the immersed part of the hull section in diametral plane; W – ship's displacement; L_w – ship's length on water-line; ρ_w – sea water density

$$X_S = \frac{1}{m} \cdot (1-\tau) \cdot T$$
$$Y_S = \frac{K_1}{m} \cdot |T| \qquad (6)$$
$$N_S = \frac{K_2}{I_z} \cdot |T|$$

where: τ – thrust deduction factor, T – propeller thrust, K_T – specific thrust coefficient,

$$X_R = -\left(\frac{1}{2}\rho_w S_p C_{xp1} v_s |v_s| + c \cdot C_{xp2} T\right)\frac{1}{m}$$
$$Y_R = -\left(\frac{1}{2}\rho_w S_p C_{yp1} v_s |v_s| + c \cdot C_{yp2} T\right)\frac{1}{m} \qquad (7)$$
$$N_R = l_p\left(\frac{1}{2}\rho_w S_p C_{yp1} v_s |v_s| + c \cdot C_{yp2} T\right)\frac{1}{I_z}$$

where: c – constant coefficient (c = 0.74), S_p – rudder blade surface; l_p – distance between rudder axis and own ship mass centre; v_s – speed of the own ship with respect to water; C_{xp1}, C_{xp2}, C_{yp1}, C_{yp2} – coefficients depending on effective rudder blade incidence angle δ_E.

$$X_{SS} = X_{SSTD} + X_{SSTR}$$
$$Y_{SS} = Y_{SSTD} + Y_{SSTR} \qquad (8)$$
$$N_{SS} = N_{SSTD} + N_{SSTR}$$

where: X_{SSTD}, Y_{SSTD}, N_{SSTD} – forces and moment from bow thruster, X_{SSTR}, Y_{SSTR}, N_{SSTR} – forces and moment from stern thrusters.
The model of external disturbances includes forces and moments from wind, waves, and sea current, defined by the following equations:

$$X_Z = X_w + X_f + X_p$$
$$Y_Z = Y_w + Y_f + Y_p \qquad (9)$$
$$N_Z = N_w + N_f + N_p$$

The equations composing the presented mathematical model of the B–481 vessel are solved using a method based on the Runge-Kutta algorithm, presented in [5].

5 Results

Simulation tests of the algorithm operation made use of the mathematical model of the ship B- 481. Problems which were the object of examination in the tests included synchronisation of motion of the ships and changing the distance between them in the formation.

Ship trajectories during the simulation are shown in Fig. 5.1a. The Leader and the Follower start from different points. Then the synchronisation phase takes place in which the ships manoeuvre to create a parallel formation. The set distance between the ships was equal to 50 meters. Courses and speeds are shown in Figs 5.1b and 5.1c. The synchronisation phase ends when the speed of the two ships is equal.

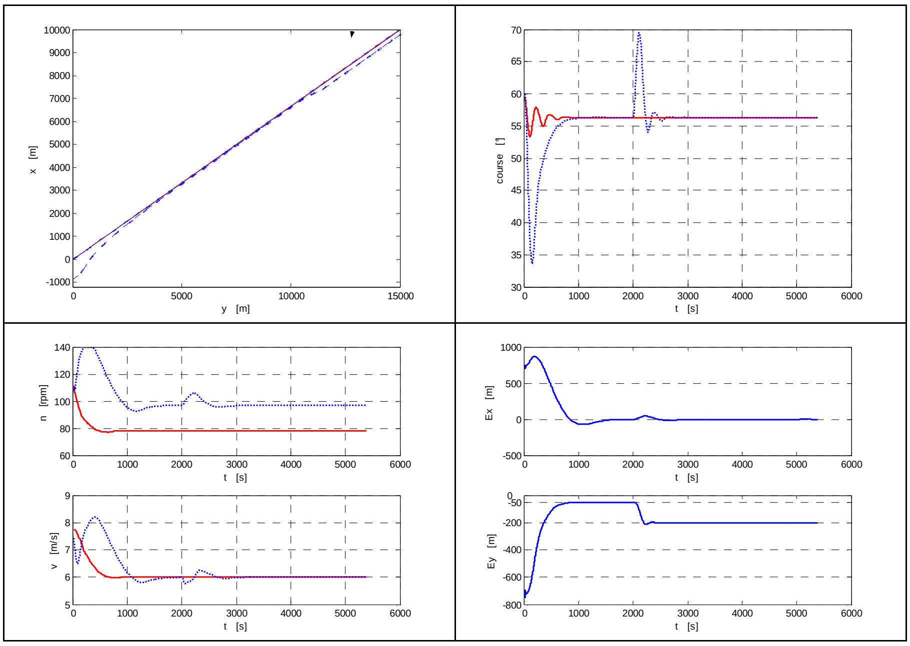

Figure 5.1. Simulation results: a) ship trajectories: solid line – Leader, dotted line – Follower, b) ship courses: solid line – Leader, dotted line – Follower, c) Ship rotational speed (n) and longitudinal speed (v): solid line – Leader, dotted line – Follower, d) measurement error values: E_x – longitudinal, E_y – lateral

Ships' behaviour was also examined during the change of the distance between them in the formation (change from 50 m to 200 m during t=2000 s). Parameters of Leader's motion were not changed. The Follower moved apart of the Leader to reach the distance of 100 meters.

Distance error curves are shown in Fig. 5.1d. E_x represents the difference in the distance between the Leader and the Follower along the X axis, while E_y the same difference along the Y axis. The error E_y is to tend to zero, while E_x is to tend to the assumed distance between the ships. Actual values of the errors are calculated using the formula:

$$\begin{bmatrix} E_Y \\ E_x \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x_L \\ y_L \end{bmatrix} - \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x_F \\ y_F \end{bmatrix} \tag{10}$$

where: (x_L, y_L) - Leader's position coordinates, (x_F, y_F) - Follower's position coordinates, α - assumed trajectory course.

6 Conclusions

The article presents the Leader-Follower algorithm making use of fuzzy course and speed controllers for ship control. The advantage of the presented system in small number of data to be transferred between the ships, with the Leader being the transmitting ship.

The algorithm was tested numerically. Firstly, the synchronisation time of the ships moving as one formation was tested. Then, change of distance between the ships in the formation was checked. The algorithm passed the test – the ships successfully kept the set distance between them.

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Modeling