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Output Adaptive Controller Design for Robotic Vessel with Parametric and Functional Uncertainties*

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***Abstract*— The problem of controlling for robotic boat with unknown parameters and unmeasurable velocity and acceleration is addressed in this paper. The controller design is based on the output robust control law. It was modified with adaptation algorithms, which allowed to eliminate a static error despite parametric and functional uncertainties. As result, the regulator minimized static error compared to robust controller. The efficiency of the proposed algorithm was illustrated by the experimental approval using the robotic boat model in the task of ellipse path movement. There is comparison between of robust controller and adaptive version in the paper.**

I. INTRODUCTION

At the present time cyber-physical systems are becoming increasingly important. They are network of computational and physical interconnected elements. Cyber-physical systems are able to adapt and reconfigure to changing external conditions. Mobile technical systems are cyber-physical systems too. These technical systems provide the transportation of cargo. Significant volume of cargo is accounted for by sea routes, which is due to the low cost and high carrying capacity of surface vessels. According to statistics 2016-2017 the volume of sea cargo transportation in Russia increased significantly. Therefore, sea transport system is significant interest. The more difficult control system is dynamic control system for movement of surface transport objects. Such control systems solve wide range of problems, including stabilization of longitudinal and lateral speeds of movement and stabilization of all coordinates (longitude, latitude, course) in a neighbourhood of the given values.

Problems of dynamic control movement are important in science. T.I. Fossen has a lot of experiments, papers and works, which devoted to ships control matters [1]. A.R. Dahl solved problems of control marine vessel [2], [3]. Zhang, B. and Liu, S. found solution of planning expected-time optimal paths for target search by robot [4].

At first we created the model of surface vessel for solution of control system. Having the model let to make experiments and prove theoretical results. Such as dynamic position system for surface vessel is in paper [5] where there is the description of program for modeling. The methods of decomposition of the model are described in [6]. The next step was development of robust control law [7]. One of the various of control algorithm was described in [8]. This paper is devoted to experiment, where we researched adaptive control system.

There is the problem in the Section I. The description of robotic model is in the Section II. There is the problem statement in the next Section III. Analysis of the plant model is in Section IV. Section V is design new control algorithms. The results of computer simulation of obtained control laws are shown in Section VII. Section VIII is the experimental study of the control algorithm with the model of surface vessel. Finally, the work is summarized in Conclusions.

Fig. 1. Robotic boat model

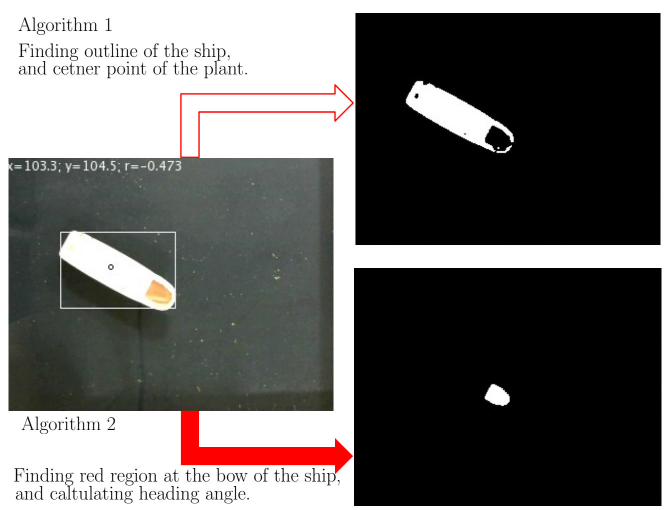

Fig. 2. Computer vision system and algorithms for calculate coordinates.

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II. ROBOTIC BOAT SETUP

It is necessary to describe the robotic model of vessel, which was created for experiments [9]. There is the photo of model on the Fig.1.Experimental stand consists of robotic boat model, digital camera with the tripod, computer, pool.

The model is hand made copy of the real vessel. It is represented at a scale of 1 : 32, so dimensions are $(0.432\times0.096\times0.052)m$. There are two tunnel thrusters on the bow and stern and the main engine. The hardware are exclusive and consists of three printed-circuit boards with microcontrollers for control, main chip is AT-mega32 from Atmel, Li-Pol battery, Bluetooth module for wireless communication with laptop.

The pool represents workspace for the boat. It holds about $150L$ of water with dimensions $(1.50\times1.10\times0.1)m$. The internal surface is painted with dark color for simplification of the computer vision.

On real ships the coordination is defined by satellite navigation systems, but when experiments are made in laboratory in the building, it is impossible to use navigation systems. It is necessary to use local coordinate system for real one simulation in this case. The digital camera is used for simulating satellites. Digital camera attached to the tripod above the pool. Image transmit to laptop, where coordinates of model of ship calculating using algorithms (Fig. 2).

III. PROBLEM STATEMENT

The simplest way to mathematically describe model of robotic vessel is using the linearized Nomoto's 2nd-order model [1], [10].

$$W(p) = \frac{K(1+T_3p)}{p(1+T_1p)(1+T_2p)}, \quad (1)$$

where $K, T_1, T_2, T_3 = \{x, y, \psi\}$ are plant parameters, which may be unknown. Impose the following assumptions.

Assumption 1: An object (1) is minimum-phase.

Assumption 2: Only the output variable is available for measurements. Its derivatives are unmeasurable.

Assumption 3: The relative degree of the plant model $\rho = n - m = 2$ is assumed to be known.

The purpose of this paper is development an output adaptive control algorithm for robotic boat movement along the ellipse trajectories with minimal deviation

$$\lim_{t\to+\infty} x^* - x(t) < \epsilon_x, \quad (2)$$

$$\lim_{t\to+\infty} y^* - y(t) < \epsilon_y, \quad (3)$$

$$\lim_{t\to+\infty} \psi^* - \psi(t) < \epsilon_\psi \quad (4)$$

under the influence of an external disturbance.

IV. ANALYSIS OF PLANT MODEL

Position and orientation of the model of vessel can be specified by three numbers: x and y and angle ψ, which usually called heading in marine navigation and control systems, and all it linear coordinates. Our ship has the three controlled actuators - two thrusters and the main engine, so there will be three output variables: $x(t)$, $y(t)$, $\psi(t)$. Let describe mathematically by the MIMO model of the form

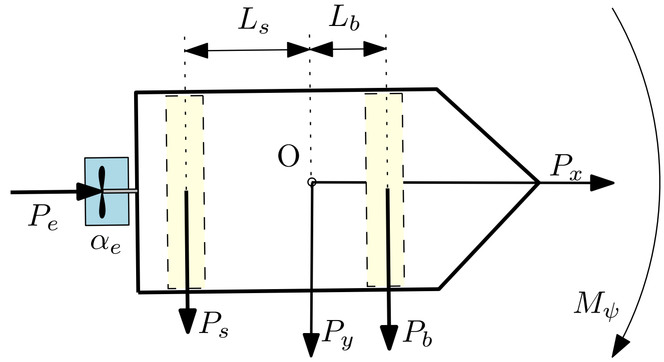


Fig. 3. Generalized forces $P_x(t)$, $P_y(t)$ and moment $M_\psi(t)$

$$x(t) = F(P_e, P_b, P_s, \alpha_e), \quad (5)$$

$$y(t) = G(P_e, P_b, P_s, \alpha_e), \quad (6)$$

$$\psi(t) = H(P_e, P_b, P_s, \alpha_e), \quad (7)$$

where P_e, P_b and P_s are the inputs of the main engine, bow thruster, stern thruster respectively, α_e is the value of steering.

The main engine creates the power of P_e. The main engine is switched on for movement along the x axis. We obtain that the force P_x depends only on P_e. At the same time for movement along the y axis, two thrusters are activated which create the forces P_b and P_s, respectively. We get that the total force vector along the y axis depends on the sum of the forces P_b and P_s. The moment of rotation M_ψ is conditioned by the torque of the main engine P_eL_e multiplied by the steering angle α_e plus moments of forces each of the thrusters P_sL_s and P_bL_b

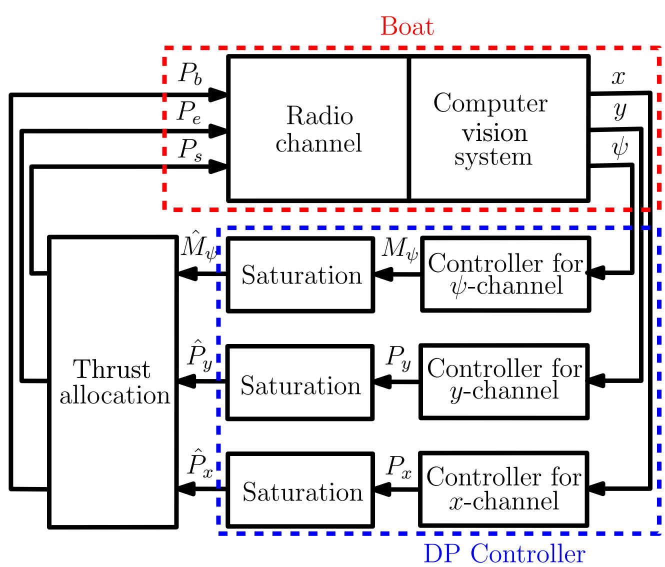


Fig. 4. Generalized forces $P_x(t)$, $P_y(t)$ and moment $M_\psi(t)$

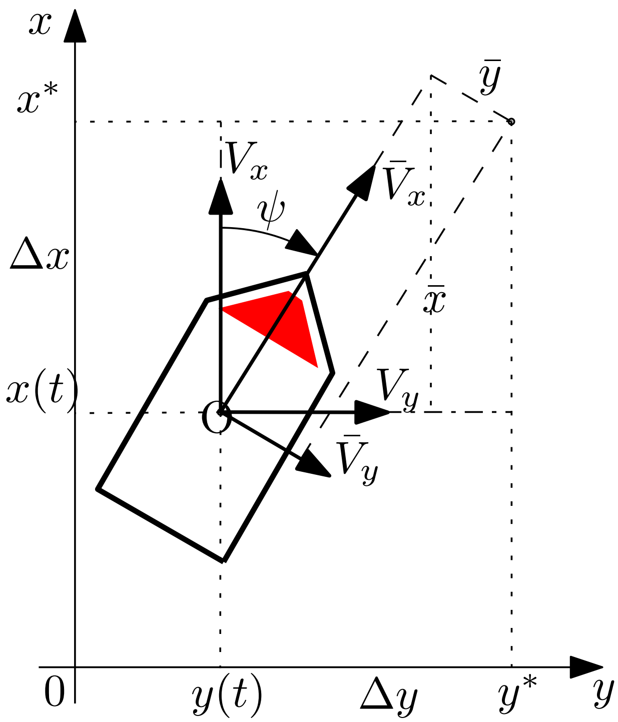


Fig. 5. Coordinate system

$$P_x(t) = P_e(t), \tag{8}$$
$$P_y(t) = P_b(t) + P_s(t), \tag{9}$$
$$M_\psi(t) = -\alpha_e(t)P_e(t)L_e + P_b(t)L_b + P_s(t)L_s, \tag{10}$$

where $P_x(t)$, $P_y(t)$ and $M_\psi(t)$ are the generalized forces and moment (see Fig. 3), L_e, L_b and L_s are distances from the canter of mass to the main engine, bow and stern respectively.

Fig. 4 shows all interconnection of the closed-loop system with the computer vision used for feedback. Output variables of the computer vision system are the linear coordinates $x(t)$, $y(t)$. It is necessary to recalculate from absolute coordinate system (O, X, Y) and heading angle $\psi(t)$ to the local coordinates $\overline{x}(t)$ and $\overline{y}(t)$ of the system $(\overline{O}, \overline{X}, \overline{Y})$ (Fig. 5) attached to the boat and error $e_\psi(t)$ as follows

$$\begin{bmatrix}\overline{x}(t)\\ \overline{y}(t)\end{bmatrix} = \begin{bmatrix}\cos(\psi) & \sin(\psi)\\ -\sin(\psi) & \cos(\psi)\end{bmatrix}\begin{bmatrix}x^* - x(t)\\ y^* - y(t)\end{bmatrix}, \tag{11}$$
$$e_\psi = \psi^* - \psi(t), \tag{12}$$

where x^*, y^* and ψ^* are the desired coordinates and heading. These obtained signals can be used in controller designed on the computer. In turn its outputs correspond to $P_x(t)$, $P_y(t)$ and $M_\psi(t)$. Call them virtual control inputs as they cannot be used for control directly. In is important to note, that they should be saturated with the limits [–127; 127] due to the hardware constraints.

V. CONTROL DESIGN

Various controllers are designed in this section. The obtained results are summarized and compared to each other.

The first step is design of nominal linear controller under the assumption that the inputs are unbounded. As the only available signals are the output variables $x(t)$, $y(t)$ and $\psi(t)$ and their derivatives are unmeasurable. It is suitable to use the robust output approach described and proved for linear plants in [11]

$$u(t) = -\alpha(p)(k + \kappa)\hat{y}(t), \tag{13}$$

where $\alpha(p)$ is Hurwitz polynomial of degree $(\rho - 1)$, $k(t)$ - adjustable parameter, there is positive parameter κ for non-linearity compensation, function $\hat{y}(t)$ - evaluation of the output variable. The function $\hat{y}(t)$ is calculated by the algorithm

$$\begin{cases}\dot{\xi}_1 = \sigma\xi_2,\\ \dot{\xi}_2 = \sigma\xi_3,\\ \cdots\\ \dot{\xi}_{\rho-1} = \sigma(-k_1\xi_1 - \cdots - k_{\rho-1}\xi_{\rho-1} + k_1 y),\end{cases} \tag{14}$$
$$\hat{y} = \xi_1, \tag{15}$$

where $\sigma > k + \kappa$ and parameter k_i are chosen from the condition of exponential stability of the system. Then make new adaptive control algorithm. We choose the control law in a new form

$$u(t) = -\alpha(p)[k(t)\hat{y}(t)], \tag{16}$$
$$\dot{k}(t) = \gamma_k\hat{y}^2(t), k(0) > 0, \tag{17}$$

where $\gamma_k > 0$ is positive coefficient.

Remark 1: Notice the coefficient k is constantly increasing. To avoid its increasing, we can reduce the coefficient to zero with the appearance of new control action. Besides we can change expression (17) as follows

$$\dot{k}(t) = \gamma_k\hat{y}^2(t) - \zeta_k(k(t) - k(0)), k(0) \geq 1 \tag{18}$$

where ζ_k is the positive coefficient. With such a modification parameter k will increase at the beginning, and at the end of the transient processes, it will decrease and reach the initial conditions $k(0)$.

Variable $\hat{y}(t)$ can be found as

$$\hat{y}(t) = h^T\xi(t), \tag{19}$$
$$\dot{\xi}(t) = \Gamma_\sigma\xi(t) + d_\sigma y(t), \tag{20}$$

where

$$\Gamma_\sigma = \begin{bmatrix}0 & 1 & \cdots & 0\\ 0 & 0 & \cdots & 0\\ \vdots & & & \\ 0 & 0 & \cdots & 1\\ -k_1\sigma^{\rho-1} & -k_2\sigma^{\rho-2} & \cdots & -k_{\rho-1}\sigma\end{bmatrix},$$
$$d_\sigma = \begin{bmatrix}0\\ 0\\ \vdots\\ 0\\ k_1\sigma^{rho-1}\end{bmatrix}, h = \begin{bmatrix}1\\ 0\\ \vdots\\ 0\\ 0\end{bmatrix},$$

where coefficients k_i, $i = \overline{1, (\rho_1)}$ are chosen from Hurwitz conditions matrix Γ_σ when $\sigma = 1$.

Remark 2: Notice the characteristic polynomial of the matrix Γ_σ when $\sigma = 1$ has the form

$$D(p) = p^{\rho-1} + k_{\rho-1}p^{\rho-2} + \cdots + k_2 p + k_1, \qquad (21)$$

which means that the choice of coefficients k_i, $i = \overline{1, (\rho_1)}$ can be satisfied from the Hurwitz condition of the polynomial (21).

We proceed to new basis of the system (19), (14)

$$\bar{\xi}(t) = T\xi(t), \qquad (22)$$

$$T = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & \sigma^{-1} & \cdots & 0 \\ \vdots & & & \\ 0 & 0 & \cdots & \sigma^{-\rho-2} \end{bmatrix}. \qquad (23)$$

Consider the error vector

$$\eta(t) = hy(t) - \bar{\xi}(t). \qquad (24)$$

Set the adaptation law for parameter σ by the following tuning algorithm

$$\dot{\sigma}(t) = \gamma_\sigma \eta^T(t)\eta(t), \qquad (25)$$

with some coefficient $\gamma_\sigma > 0$.

VI. NUMERICAL EXAMPLE

Consider the model of motion of a displacement vessel, which were described earlier (Nomoto's 2nd-order model) in the new form

$$\ddot{y}(t) = -\frac{\varpi_0}{T} + \frac{k_0}{T}u(t) + \delta(t) \qquad (26)$$

where T is the time constant, ϖ_0 and k_0 are the transmission coefficients, and $\delta(t)$ is the generalized disturbance.

The relative degree of the object is $\rho = 2$. We choose Hurwitz characteristic polynomial of the matrix Γ_σ for $\sigma = 1$ for

$$D(p) = p + 1. \qquad (27)$$

In the tracking mode the robust algorithm (13) takes the form

$$u(t) = -\alpha(p)(k + \kappa)\hat{y}(t), \qquad (28)$$

$$\hat{y}(t) = \xi(t), \qquad (29)$$

$$\dot{\xi}(t) = -\sigma\xi(t) + \sigma(y(t) - y^*), \qquad (30)$$

where

$$\Gamma_\sigma = [-\sigma], \quad d_\sigma = [\sigma], \quad h^T = [1]. \qquad (31)$$

The next step is modifying the algorithm (16) to the adaptive version. Adaptation algorithms (17), (25) to adjust $k(t)$ and $\sigma(t)$, respectively, taking into account the conditions $k(0) > 0$ and $\sigma(0) \geq 1$. We differentiate the function $k(t)\hat{y}(t)$ successively $\rho - 1$ times

$$\begin{aligned} u(t) &= -\alpha(p)[k(t)\hat{y}(t)] = \\ &= -\frac{d}{dt}[k(t)\hat{y}(t)] - k(t)\hat{y}(t) = \\ &= -\gamma_k\xi^3(t) - k(t)\dot{\xi}(t) - k(t)\hat{y}(t). \end{aligned} \qquad (32)$$

To avoid unlimited growth of the functions $k(t)$ and $\sigma(t)$ for small deviations from the equilibrium position, we modify the adaptation laws (17), (25) as follows

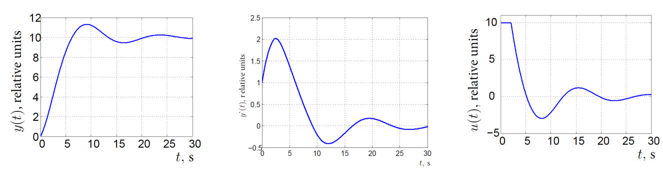
$$\begin{cases} \dot{k}(t) = \gamma_k\hat{y}^2(t), |\hat{y}(t)| \geq \epsilon_i k(0) > 0, \\ \dot{k}(t) = 0, \quad |\hat{y}(t)| < \epsilon_i, \end{cases} \qquad (33)$$

$$\begin{cases} \dot{\sigma}(t) = \gamma_\sigma(y(t) - \xi(t))^2, |\hat{y}(t)| \geq \epsilon_i k(0) > 0, \\ \dot{\sigma}(t) = 0, \quad |\hat{y}(t)| < \epsilon_i. \end{cases} \qquad (34)$$

VII. SIMULATION

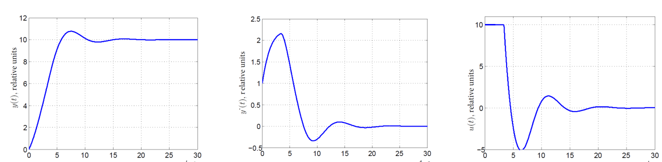
The computer simulation of the results was carried out. We considered the robust algorithm (28), and the adaptive algorithm (32) for different parameters of the system. In all the experiments we used the parameters $T = 5$, $k_u = 0.5$, $\varpi = 1$, $\epsilon = 0.5$. Parameters of the system

1) The robust algorithm, $k + \kappa = 2$, $\sigma = 10$, $y^* = 10$, $\delta = 0$. Fig. 6.
2) The robust algorithm, $k + \kappa = 5$, $\sigma = 15$, $y^* = 10$, $\delta = 0$. Fig. 7.
3) The robust algorithm, $k + \kappa = 5$, $\sigma = 15$, $y^* = -5$, $\delta = 0$. Fig. 8.
4) The adaptive algorithm, $k(0) = 0$, $\sigma(0) = 0$, $\gamma_k = 0.1$, $\gamma_\sigma = 0.2$, $y^* = 6$, $\delta = 0$
5) The adaptive algorithm, $k(0) = 0$, $\sigma(0) = 0$, $\gamma_k = 1$, $\gamma_\sigma = 10$, $y^* = 6$, $\delta = 2 + 3sin1.5t$



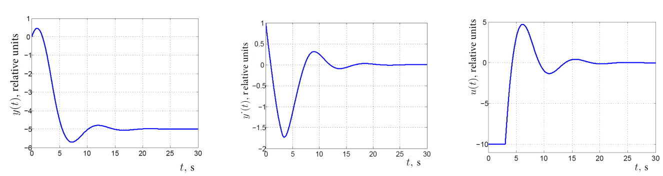
a) $y(t)$ b) $\dot{y}(t)$ c) $u(t)$

Fig. 6. Simulation result for control law (28)– (31).



a) $y(t)$ b) $\dot{y}(t)$ c) $u(t)$

Fig. 7. Simulation result for control law (28)– (31).



a) $y(t)$ b) $\dot{y}(t)$ c) $u(t)$

Fig. 8. Simulation result for control law (28)– (31).

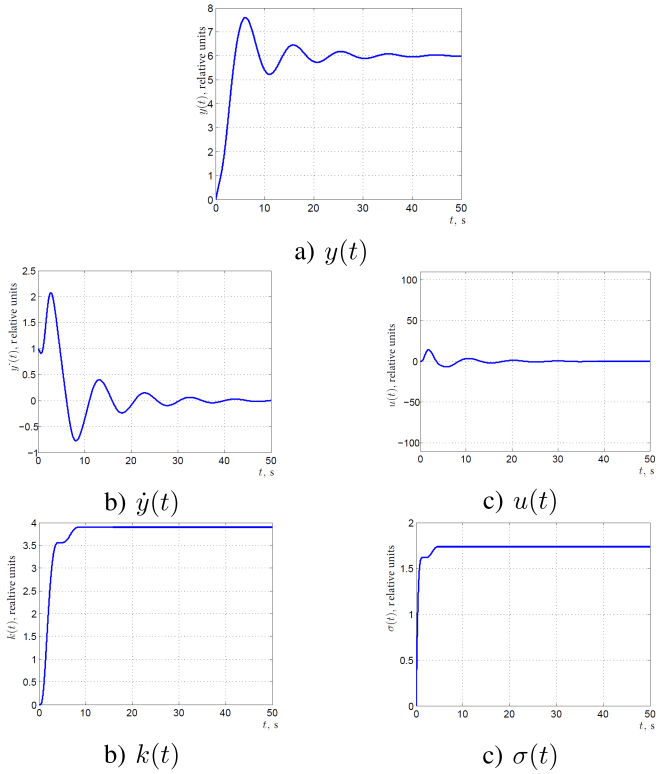


Fig. 9. Simulation result for control law (32), (29)– (31), (33)– (34).

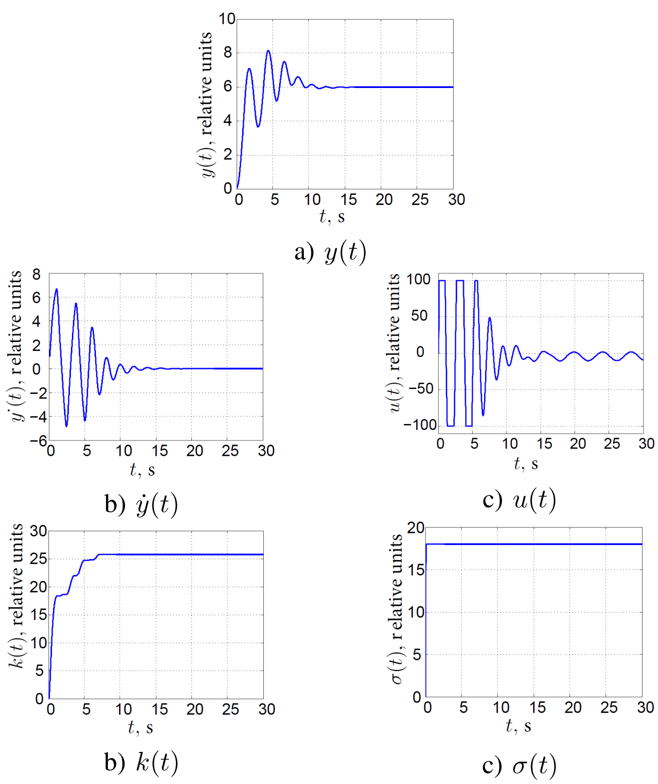


Fig. 10. Simulation result for control law (32), (29)– (31), (33)– (34).

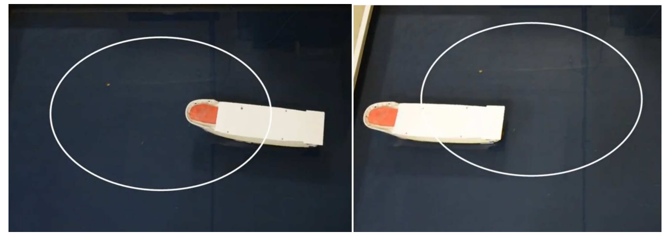


Fig. 11. Robotic vessel in experiment with ellipse trajectory

The robust algorithm reaches a predetermined value in about 25 seconds regardless of parameters. At the same time the adaptive algorithm converges during 15 seconds, despite the presence of disturbances and constraints on the input.

VIII. EXPERIMENAL APPROVAL

After that computer modeling algorithms were tested with the surface vessel model. It was necessary to distribute the control action between the drives. The virtual inputs should be transformed to the real ones

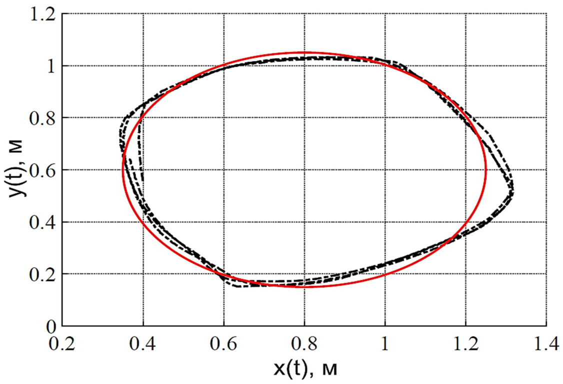
$$P_e(t) = P_x(t), \tag{35}$$
$$P_b(t) = P_y(t) - P_s(t), \tag{36}$$
$$P_s(t) = \frac{-\alpha_e(t)P_x(t)L_e + P_y(t)L_b - M_\psi}{L_b - L_s}. \tag{37}$$

For the experiment the trajectory in the form of the ellipse was given

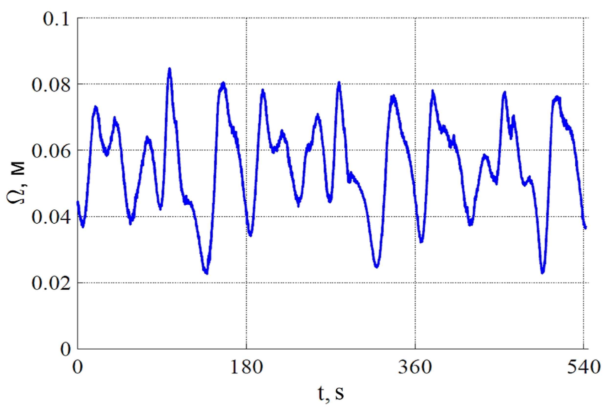
$$y_x^* = sin(t)$$
$$y_y^* = 2cos(t)$$

Fig. 11 shows the trajectory placed on an image obtained from a computer vision system. Stages of the experiment

1) The robust regulator $u(t) = -\alpha(p)(k+\kappa)\hat{y}(t)$, Fig. 12.
2) The adaptive controller
$u(t) = -\gamma_k\xi^3(t) - k(t)\dot{\xi}(t) - k(t)\hat{y}(t)$, Fig. 13.
3) for both experiments, the norm of the deviation of the coordinate is determined by the formula
$\Omega = \sqrt{(x - x^*)^2 + (y - y^*)^2}$
4) Disscussion. There are next experimental diagrams: 1) trajectory and norm of the deviation of coordinates for the robust algorithm 12 and 2) the trajectory and rate of deflection coordinates to the adaptive controller 13. Both of them has shown quality results, and robotic model performed the task motion along the given trajectory. But robust algorithm has the norm of deviation of coordinates, which is 0,082m, at the same time the adaptive algorithm showed the best results, because the rate of abnormalities for this control algorithm were only 0.07m. The width of the model is just 0,096m, so such difference is quite critical.

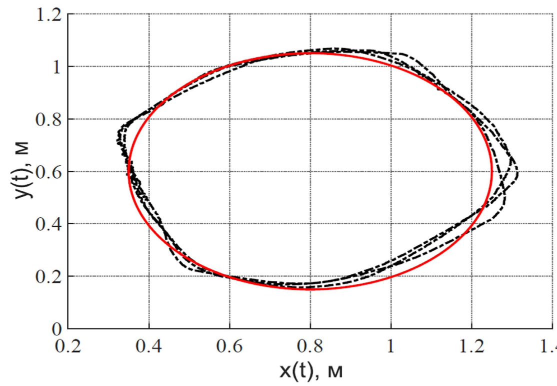


a) Trajectory of motion

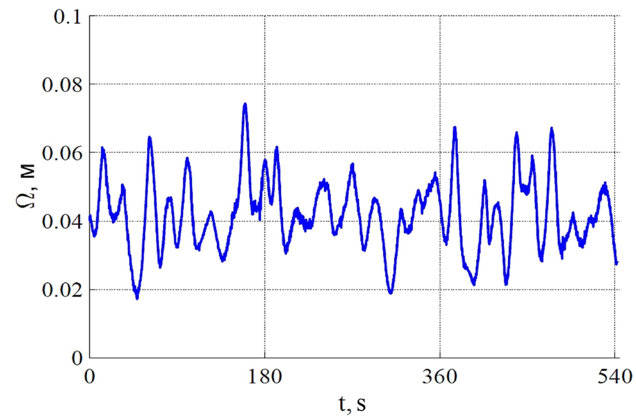


b) Norm of deviation of coordinates

Fig. 12. Plots of trajectory of motions and norm of deviations of coordinates for robust control low (28)–(31).



a) Trajectory of motion



b) Norm of deviation of coordinates

Fig. 13. Plots of trajectory of motions and norm of deviations of coordinates for adaptive control law (32), (29)– (31), (33)– (34).

IX. CONCLUSIONS

This practical work has shown that both of the algorithm can be used for controlling the model. Both control lows coped the task, though the limit the control because of the technical specificity of the model. However, the adaptive version of the control algorithm shows better results, that is critical in the problems of ships controlling. Improving of results will be continued in the next experiment.

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