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Unmanned Powerboat Motion Terminal Control in an Environment with Moving Obstacles

Abstract

The major point for consideration throughout this paper is controlling the motion of an unmanned powerboat in an obstructed environment with stationary and moving objects. It offers a procedure for the terminal control law development based on the powerboat programmed motion trajectory in a polynomial form and proposes position-trajectory-based control algorithms. A hybrid method based on virtual fields and unstable driving modes, taking into account powerboat speeds and obstacles, is used to plan motion trajectories for obstacle avoidance. There were experiments carried out to test the developed methods and algorithms meanwhile estimating the energy consumption for control, the length of the trajectory and the safety indicator for obstacle avoidance. The novelty of the proposed approach lies in the method used to develop a local movement trajectory in the field with obstacles and in the hybridization of trajectory scheduling methods. This approach allows us to achieve a given safe distance when avoiding obstacles and virtually eliminate the chances of an emergency collision. The presented results can be used in systems of boats autonomous motion control and allow safe stationary and dynamic obstacles avoidance.

Keywords: *terminal control, potential field method, position-trajectory control, quality indicators, speed control, unmanned powerboat*

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Терминальное управление безэкипажным катером в среде с подвижными препятствиями

В данной работе основным предметом исследования является система управления движением безэкипажного катера в неопределенной среде со стационарными и подвижными препятствиями. Актуальность разработки такой системы обусловлена тем, что безэкипажные катера функционируют вблизи портов, судоходных фарватеров и в других местах с плотным движением других судов. При этом из-за отсутствия экипажа нет возможности согласовывать движение с другими судами, поэтому система управления такого безэкипажного катера должна прокладывать маршрут, учитывая требования к своему положению в каждый момент времени.

В связи с этим в статье предложена процедура разработки терминального закона управления на основе программируемой траектории движения катера в полиномиальной форме, на основе которой реализованы позиционно-траекторные алгоритмы управления. При этом программная траектория строится как решение задачи терминального управления в сильной постановке, а позиционно-траекторный регулятор отрабатывает полученную траекторию в рамках слабого терминального управления. Для учета препятствий при планировании траектории используется гибридный метод, основанный на виртуальных полях и неустойчивых режимах движения с учетом скоростей и условий движения безэкипажного катера. В работе приводятся результаты численных и натурных экспериментов по апробации разработанных методов и алгоритмов. Получены оценки энергозатрат на управление, длины траектории и показателя безопасности при обходе препятствий.

Новизна предлагаемого подхода заключается в использовании нового метода построения локальной траектории движения в поле с препятствиями и в гибридизации методов планирования траекторий. Такой подход позволяет обеспечить заданную безопасную дистанцию при обходе препятствий и практически исключить вероятность аварийного столкновения. Представленные результаты могут быть использованы в системах автономного управления движением катеров и позволяют безопасно обходить стационарные и динамические препятствия.

Ключевые слова*: терминальное управление, метод потенциальных полей, позиционно-траекторное управление, показатели качества, управление скоростью, безэкипажный катер*

Introduction

Autonomous moving objects (robots) are controlled in two-dimensional and tridimensional space, as well as in various environments (in air, above water, under water, on the surface). The control is implemented in automatic as well as automated modes in both deterministic defined and non-defined environments. Automatic movement of moving objects (MO) can be performed either along the prescheduled trajectories or in an unspecified environment with specified coordinates of the goal point with stationary and moving obstacles. There may be no time limits for the goal being reached; however, there may also be a requirement for the MO achieving the goal within the time set. Multiple practical examples can be cited with relation to controlling a single or a group of MOs in different environments under different conditions for the goal achievement. One example is an aircraft, when being autopiloted, is capable of performing an autonomous flight along a prescheduled trajectory and of independent landing onto a specially prepared aerodrome using navigation systems [1]. Other instances include quadcopters, which will automatically fly along a predetermined trajectory, and robotic sea powerboats, which are already in service with a number of countries. A good example is Tesla autopilot vehicles [2] and similar vehicles by other developers (Toyota, Volvo, Mersedes, etc.) that are already in use on the roads.

Software control systems are undergoing steady improvement, and nowadays control systems can identify the environment [3—7], solve problems of moving a single MO and groups of MOs using analytical methods [8—10], or, under significant uncertainty, using neuro-fuzzy networks, genetic algorithms, contingency approach and methods aimed at enhancing the specialists' knowledge of [11—15].

Even though up-to-date scientific methods and MO control technologies allow solving MO movement problems in complex, non-deterministic environments, the terminal control problem remains quite relevant [16]. When solving the terminal control problem, the MO setting off from the starting point is supposed to reach the goal end point at a set time, given the fact that the operating environment is uncertain, which is the major focus of this paper.

The task of terminal control remains relevant and has been the subject of consideration in multiple scientific papers, since different methods have been suggested to solve this problem. One solution to the problem has been by using sliding modes, for example, paper [17] covers a sliding mode implementation in some classes of nonlinear control systems. Another solution suggests using nonlinear control models, for example, paper [18] describes the two-mode nonlinear model implementation of control over a nonlinear object under given constraint concerning the state and control. The control is performed with several parameters being selected a priory, which evaluate the terminal area and parameters. When the object under control moves, these parameters are optimized in real-time mode by the terminal controller to achieve the goal set. The solution of the terminal control problem can also be based on a special kind nonlinear similarity conversion, which means with control over the state feedback, the transition of the initial system into a linear and stationary system is ensured in a special way [19]. This is the task for weak terminal control over discrete nonlinear systems with scalar output.

The problem of planning the motion trajectories of the mobile objects in environments with obstacles has been considered in in numerous papers. A lot of papers considered the implementation of the potential field method. For example, the paper [20] proposed and analyzed control algorithms in environments with moving and stationary obstacles, providing MO control that prevents it from falling into the local minima of the potential field. In the paper [21], the application of methods for trajectories planning of moving objects based on fuzzy logic was considered. The authors have created elementary MO behavior models, and proposed a mechanism for their integration for MO management in an uncertain environment.

They pay attention to the use of unstable traffic patterns when scheduling MO trajectories. For instance, the paper [22] illustrates the use of control actions which stabilize robot trajectories in obstacle-free zones, as well as the application of the third Lyapunov theorem (the instability theorem) when a moving object is spotted in zones of stationary or non-stationary obstacles at distances less than the tolerable. The symbiosis of unstable driving modes and the method of potential fields can be considered, which allows the creation of hybrid control methods, as shown in papers [23, 24].

The analysis of known works enables us to identify prospects for further research in the field of terminal control using the potential field method, for scheduling the movement of an unmanned powerboat in case obstacles appear, and a method based on unstable modes, in case of a dangerous approach to them, which is the subject of this article.

The paper is organized as follows. Section 2 presents a mathematical model of a vessel, description of the onboard control system, and the synthesis of terminal control. Problem statement is given. Section 3 describes the obstacle avoidance method. Section 4 presents experimental results.

The mathematical model of the vessel and the synthesis of terminal control

Fig. 1 represents the experimental prototype of the vessel. The powerboat features the following overall dimensions: height 0.6 m, width 0.7 m, length 1.8 m. The superstructure (bulkhead) hosts the engine control unit 1, the autonomous motion control unit 2, camera information processing unit 3, batteries, WiFi router and integrated navigation system (see fig. 2). The mast places 3 cameras, WiFi and GPS modules.

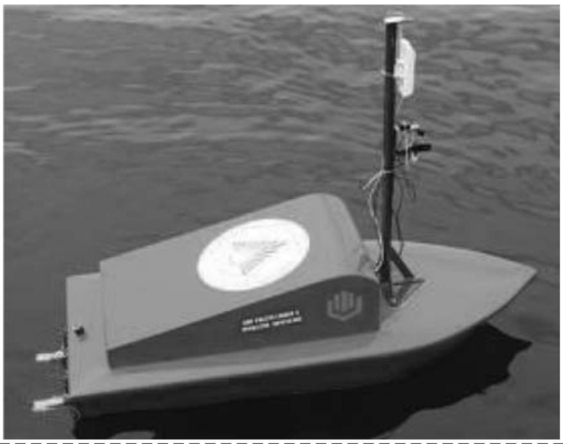

Fig. 1. An appearance of the unmanned vessel

Let the mathematical model of the vessel, in accordance with the coordinate system presented in fig. 1, s, have the following form:

$$\dot{S} = \begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} Q, \tag{1}$$

$$M\dot{Q} = F_u(Q, S, \delta, l, t) + F_d(P, V, W) + F_\upsilon(G, A, R), \tag{2}$$

where $S = [x_{gt} \quad z_{gt} \quad \varphi]^{\mathrm{T}}$ stands for the gravity center coordinate vector of the vessel and the orienting angle in the fixed coordinate system; $Q = [V_x \quad V_z \quad \omega_y]^{\mathrm{T}}$ stands for the projection of the velocity vector on the axis of the coordinate system associated with the power boat XYZ (see fig. 3); φ signifies current course, and ω_y is the angular velocity of the vessel relative to the vertical axis OY; $F_d(P, V, W)$ — (3×1) represents the vector of non-linear dynamic elements, including Coriolis forces, $F_\upsilon(G, A, R)$ — (3 × 1) means the vector of measured and non-measurable external disturbances; M — (3×3) stand for the matrix of mass-inertial parameters, whose elements are mass, inertia moments, apparent masses $F_\upsilon(Q, S, \alpha, l, t)$ — (3 × 1) is the control forces and moments vector (l is the vector of design parameters, α is the deviation angle of engines from the X axis, t is time). A more detailed description of the mathematical model is presented in [25].

It is required to synthesize such a control algorithm that would ensure the vessel movement from

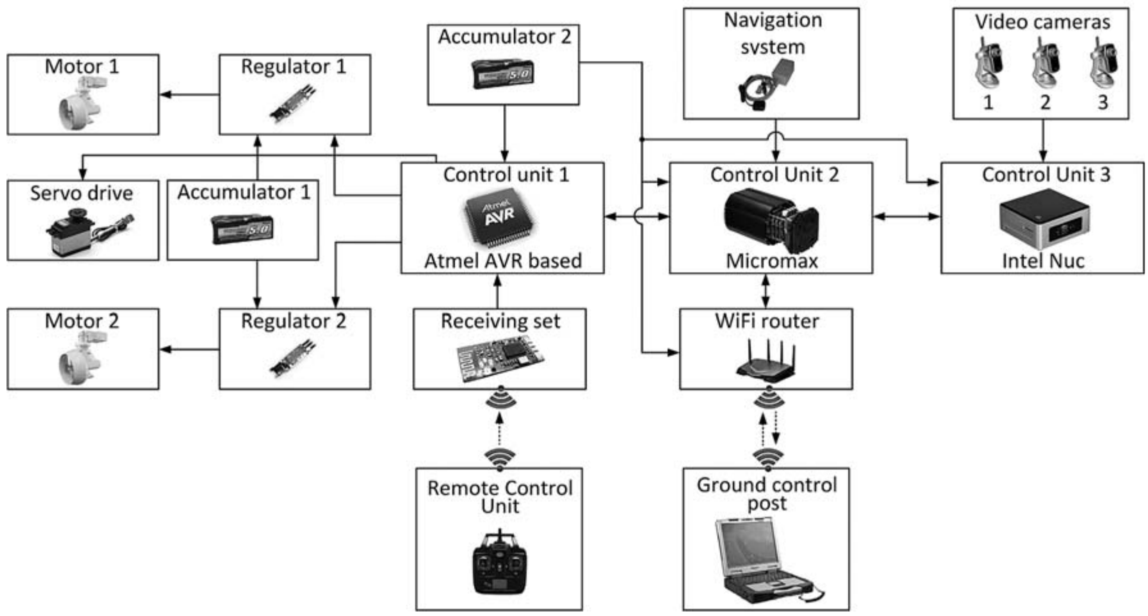

Fig. 2. Block diagram of the onboard control system

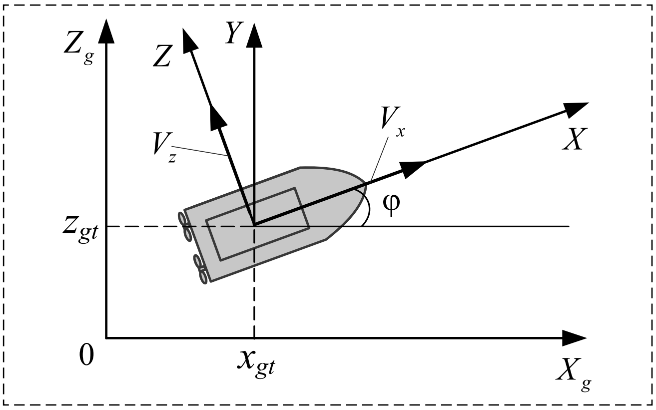

Fig. 3. The unmanned vessel coordinate system

the initial position $P_0 = (x_0, z_0)$ to the final position $P_k = (x_k, z_k)$ at a given moment of time $t = T_k$, and the speed at the moment of time $t = T_k$ should be zero, i.e.

$$Q_k = \left(V_x, V_z, \omega_y\right)^{\mathrm{T}} = 0_{3\times 1}.$$

To solve the problem of synthesizing the terminal control, we will define the programmed motion trajectory of the unmanned vessel in a polynomial form and present it in the matrix form:

$$S^* = CLS^* = CL, \tag{3}$$

where

$$C = \begin{bmatrix} x_0 & 0 & \frac{3}{T_k^2}(x_k - x_0) & \frac{3}{T_k^3}(x_k - x_0) \\ z_0 & 0 & \frac{3}{T_k^2}(z_k - z_0) & \frac{3}{T_k^3}(z_k - z_0) \end{bmatrix}, \quad L = \begin{bmatrix} 1 \\ t \\ t^2 \\ t^3 \end{bmatrix}.$$

C is a matrix of constant coefficients depending on the initial and final position of the vessel, as well as on T_k which is the specified positioning time.

The degree of the polynomial L is determined by the number of terminal parameters. In this case, these are two coordinates and the speed.

It can be also shown that:

$$\dot{S}^* = CD_1L,$$

$$\ddot{S}^* = CD_2L,$$

where $D_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \end{bmatrix}$, $D_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 \\ 0 & 6 & 0 & 0 \end{bmatrix}$.

The terminal control law is developed basing on position-trajectory algorithms [22]; to this end, the real trajectory deviation error is set from the given program in the following form:

$$\Psi_{tr} = S - S^* = S - CL.$$

Let us introduce an additional variable $\Psi = \dot{\Psi}_{tr} + T_1 \cdot \Psi_{tr}$, where T_1 is the diagonal matrix of constant dimensions (2×2), $\dot{\Psi}_{tr} = \dot{S} - CD_1L$. We also set the desired behavior of the closed-looped system in the form below:

$$\dot{\Psi} + T_2 \cdot \Psi = 0,$$

where T_2 is the diagonal matrix of constant dimension (2×2). Thus, the desired behavior of the system, expressed through Ψ_{tr}, has the following form:

$$\ddot{\Psi}_{tr} + T_1\dot{\Psi}_{tr} + T_2\left(\dot{\Psi}_{tr} + T_1\Psi_{tr}\right) = 0, \tag{4}$$

where $\dot{\Psi}_{tr} = \dot{S} - CD_1L$, $\ddot{\Psi}_{tr} = \ddot{S} - CD_2L$.

Upon substituting in (4) the equation of the vessel mathematical model (2) and expressing the corresponding control forces and moments vector F_v, we obtain the following control algorithm:

$$F_u = -MR^{-1}[\dot{R}Q - CD_2L + T_1\dot{\Psi}_{tr} + \\ + T_2(\dot{\Psi}_{tr} + T_1\Psi_{tr})] - F_d'. \tag{5}$$

To perform the stability analysis, we substitute the resulting expression (5) into the equation of the mathematical model (3).

$$\begin{cases} \dot{S} = RQ \\ \dot{Q} = R^{-1}\begin{bmatrix} \dot{R}Q - CD_2L + T_1(RR - CD_1L) + \\ +T_2(\dot{R}Q + R\dot{Q} - CD_2L + \\ +T_1\left(RQ - CD_1L\right)) \end{bmatrix} \end{cases} \tag{6}$$

We shall set the Lyapunov function in the following form:

$$V = \Psi^T W \Psi,$$

where W is a diagonal positive definite matrix of size (2×2). Then the derivative of the Lyapunov function has the form:

$$\dot{V} = -2\left[RQ - CD_1L + T_1\Psi_{tr}\right]\times \\ \times W\left[-T_2\left(Q - CD_1L + T_1\Psi_{tr}\right)\right].$$

We shall define the W matrix to be $WT_2 = G$ where G the diagonal positive definite dimension matrix of (2×2), so we obtain the following expression for the derivative $\dot{V}(x)$:

$$\dot{V} = -2\left[RQ - CD_1L + T_1\Psi_{tr}\right]\times \\ \times G\left[RQ - CD_1L + T_1\Psi_{tr}\right].$$

Since G is a positive definite matrix, the function $\dot{V}$ is negative definite at all points. It is enough just to show that the value of $Q = -R^{-1}\left(CD_1L + T_1 \cdot \Psi_{tr}\right)$ is not a solution of system (6). Thus, it can be affirmed that system (6) is asymptotically stable, taking into account the addition of Barabashin-Krasovsky [26].

Let's note that control algorithm (5) does not contain a singularity at the target point. This property is very important for terminal control systems [27, 28].

The local planning algorithms

General concept. Basing on the terminal control algorithm (5) the vessel moves in an unobstructed environment to the coordinates of the end point P_k. In case of obstacles in the field of repulsive forces of the virtual field (fig. 4), a local trajectory of circumventing the obstacle is formed and the coordinates of the unmanned powerboat are planned based on the method of potential fields, while the coordinates of the end point P_k are replaced by P_k^*. Besides, if obstacles arise in the vessel safety zone, coordinates are scheduled using the method based on an unstable driving mode. When the obstacles leave the virtual zone of repulsive forces, the regular terminal control mode is restarted, and a new of initial conditions vector is formed for the algorithm (5).

Now let us consider the methods for the powerboat coordinates planning.

Method of forming a local obstacle avoidance trajectory. When forming a local obstacle avoidance trajectory, the vision field of the vision system is divided into sectors, as shown in fig. 5. In accordance with fig. 5, the value of B determines the chord, which subtends the ends of the sector, and is equal to the radius of the safety zone of the boat.

To determine the number of sectors in the locator's view, you need to perform the following sequence of actions. First, the sector angles are calculated according to the formula:

$$\beta_s^* = 2\arcsin\left(\frac{B}{D}\right), \tag{7}$$

where β_s^* is sector angle; D — stands for the range of the sensor system of the boat.

Then their number is determined by the formula

$$N = \left\lceil \frac{\rho}{\beta_s^*} \right\rceil, \tag{8}$$

where ρ is the angle of view of the technical vision system of the boat, $\lceil \cdot \rceil$ is the operation of extracting the integer part of a number, rounded upward.

By virtue of the fact that the locator vision field must be completely covered by sectors with identical angles, sector angles have to be adjusted in accordance with the expression

$$\beta_s = \frac{\rho}{N}. \tag{9}$$

If obstacles are spotted within the sector, the latter is marked with figure of one, as being prohibited for movement; otherwise, it is marked as free. The boat movement process can be organized in this case as the following sequence of steps.

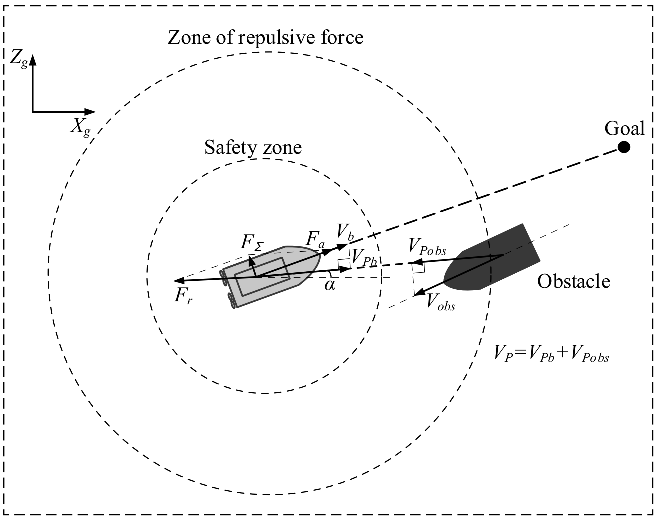

Fig. 4. Illustration of potential field forces action

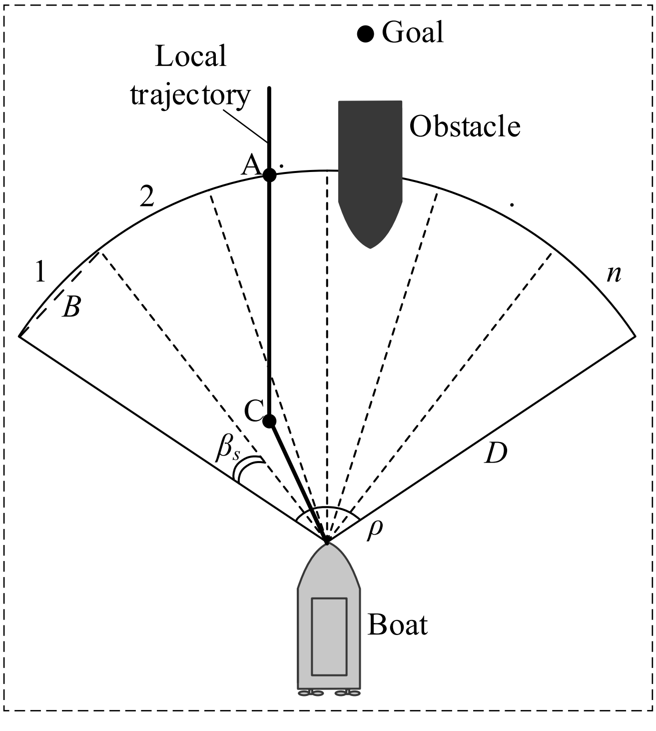

Fig. 5. The division of the vision field of the boat sensor system into sectors

Step 1. The sensory system visual field sectors are analyzed: if there is an obstacle in the sector, the sector is marked as prohibited (1), or otherwise, as free (0).

Step 2. The sector analysis towards the target point. Proceed to step 6 if the sector is marked as free (0), or to step 3 if the sector is marked as busy (1).

Step 3. Search for the nearest free sector towards the target point: if there are none, proceed to step 6, otherwise go to step 4.

Step 4. Calculation of the coordinates of point A in the middle of the sector.

Step 5. Calculate the coordinates of point C at a distance of 1/3 from the boat to point A.

Step 6. The end.

After point C becomes target for the boat, and one is used in the calculation of the potential field forces. As soon as it is reached, point A becomes the target. If all sectors of the visual field are busy, the movement direction is selected randomly beyond the vision field of the technical vision system.

The method of virtual (potential) fields. The virtual (potential) fields method is a widespread method for planning the moving objects trajectories [29, 30] due to a number of advantages, in particular:

— Low requirements for the moving object onboard computer;

— Low requirements for the moving object sensory subsystem;

— Inaccurate (approximate) information being tolerable to use, concerning the coordinates of the obstacles and the target point;

— Ample opportunities for modification.

However, alongside with the advantages, this method features a number of the disadvantages listed below:

— the emergence of areas with local minimum fields throughout which a moving object can not continue moving towards the target point;

— low efficiency when used in three-dimensional environments and in flat environments with complex obstacles;

— the impossibility of taking into account the dynamics of a moving object which results in ineffective implementation of the scheduled trajectory.

These drawbacks hinder the independent use of this method to schedule the moving objects trajectories in an environment with obstacles. Nevertheless, the considerable room for modification allow synthesizing hybrid scheduling methods that reduce the drawbacks above.

Let us consider a nonpotential field when repulsive forces depend on the moving object speed and, therefore, are non-conservative (see fig. 4).

In this paper, the components of the attracting virtual force to the target point are defined by the formula:

$$\begin{bmatrix} F_{ax} \\ F_{az} \end{bmatrix} = k\frac{\left(\begin{bmatrix} x_g \\ z_g \end{bmatrix} - \begin{bmatrix} x_r \\ z_r \end{bmatrix}\right)}{d_{rg}}, \qquad (10)$$

where x_r, z_r are the moving object coordinates; x_g, z_g stand for the target point coordinates; d_{rg} is the distance between the moving object and the target; k is the coefficient of attractive force ($k > 0$).

The distance between the moving object and the target is calculated using the expression:

$$d_{rg} = \sqrt{\left(x_r - x_g\right)^2 + \left(z_r + z_g\right)^2}, \qquad (11)$$

The components of the repulsive potential force from the obstacles are determined by the expression:

$$\begin{bmatrix} F_{rxi} \\ F_{rzi} \end{bmatrix} = -c \cdot e^{-\beta q_i} \begin{bmatrix} V_{Pi}\cos(\alpha_i) \\ V_{Pi}\sin(\alpha_i) \end{bmatrix}, \qquad (12)$$

where q_i is the distance between the moving object and the i -th obstacle; α_i is the orientation angle of the moving object in relation to the obstacle i -th obstacle; V_P is the projection of the relative velocity of the moving object and obstacle; c, β — are the repulsive force coefficients ($c > 0$, $\beta > 0$).

The orientation angle of the moving object with respect to the i-th obstacle is determined by the expression:

$$a_i = \mathrm{atan2}\left(z_{oi} - z_r, x_{oi} - x_r\right), \qquad (13)$$

where x_{oi}, z_{oi} designate the coordinates of the i-th obstacle; *atan2* is a function for calculating the tangent of an angle in the interval $-\pi < \alpha \leqslant \pi$.

The distance between the moving object and the i-th obstacle is determined by the expression:

$$d_i = \sqrt{\left(x_r - x_{oi}\right)^2 + \left(z_r + z_{oi}\right)^2}. \qquad (14)$$

After calculating the attractive force of the MO to the target point and repulsive forces from obstacles and the boundaries of the working area, the components of the resultant force of the virtual field can be found by the formula:

$$\begin{bmatrix} F_{\Sigma x} \\ F_{\Sigma z} \end{bmatrix} = \begin{bmatrix} F_{ax} \\ F_{az} \end{bmatrix} + \begin{bmatrix} \sum_i F_{rxi} \\ \sum_i F_{rzi} \end{bmatrix}. \qquad (15)$$

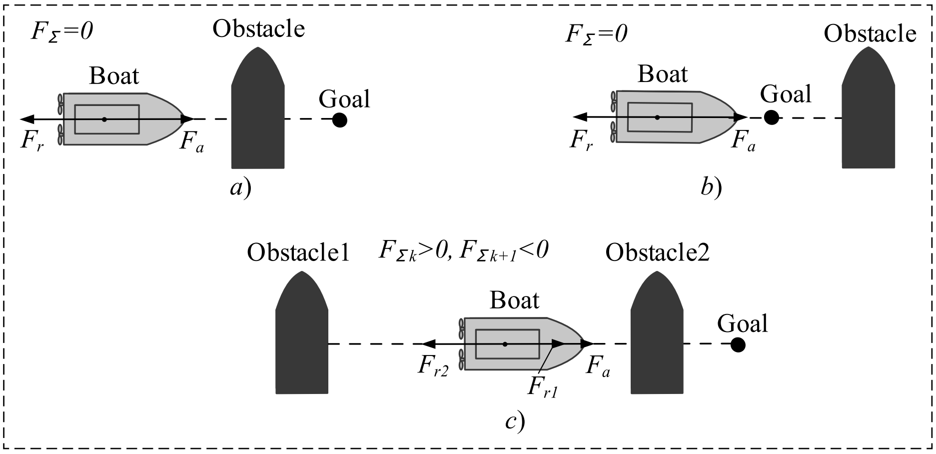

Fig. 6. Local minimum areas occurrence illustrated

The planned end point coordinates of the MO movement with the step determined by the expression:

$$\begin{bmatrix} x_p \\ z_p \end{bmatrix} = \begin{bmatrix} x_r \\ z_r \end{bmatrix} + \begin{bmatrix} F_{\Sigma x} \\ F_{\Sigma z} \end{bmatrix} \Delta t, \quad (16)$$

where Δt is the time step; x_p, z_p are the coordinates of the planned moving object trajectory.

As indicated above, one drawback of the potential field method is the possibility for a moving object to fall into the local minimum of the field. In the local minimum of the field, the configuration of the medium and the potential forces are such that the resultant force F is equal to zero at each time instant (fig. 6, a, b) or constantly changes its sign for the opposite (fig. 6, c).

Either does the moving object stop or reciprocate, but cannot move to the target point. The local minimum area of the potential field for the cases shown in fig. 6, *a, b* are determined with $F_\Sigma = 0$.

The situation presented in fig. 6, *c* can be diagnosed by analyzing the moving object direction. If the sign of the potential field resultant force F_Σ, projected onto the line, connects the moving object and the target point at k and $k + 1$ steps, it is reversed, which means the angle

$$\chi = \pi - \arccos\left(\frac{\left\langle \bar{F}_\Sigma(k) \cdot \bar{F}_\Sigma(k+1) \right\rangle}{\left|\bar{F}_\Sigma(k)\right| \cdot \left|\bar{F}_\Sigma(k+1)\right|}\right) \quad (17)$$

does not exceed some small value of ε, it is necessary to take additional steps to lead a moving object out of the field local minimum. Model experiments have established that with $\varepsilon \leqslant \pi/60$ this case is well diagnosed.

To solve the problem of getting the MO into the local field minimum, we use an approach based on the temporary replacement of the global target point with a virtual target [31].

If one of the virtual field local minimum areas is diagnosed, the virtual target point coordinates can be calculated in accordance with the expression:

$$\begin{bmatrix} x_{gv} \\ z_{gv} \end{bmatrix} = \begin{bmatrix} x_r \\ z_r \end{bmatrix} - H\sigma \begin{bmatrix} x_g \\ z_g \end{bmatrix}, \quad (18)$$

where x_{gv}, z_{gv} represent the virtual target point coordinates; σ — is the coefficient determined by the nature of the medium, the obstacles configuration and the distance between the target point and the moving object ($\sigma < 1$); H — is the rotation matrix.

$$H = \begin{bmatrix} \cos(\xi) & \sin(\xi) \\ -\sin(\xi) & \cos(\xi) \end{bmatrix}, \quad (19)$$

where ξ is the angle set randomly from $\pm\pi/2$.

The time t_z of the reverse substitution of the virtual target point for the global one is determined by the moving object dynamics and the operating environment state. It is necessary to choose t_z so that the moving object does not return to the potential field local minimum area. Thus, the placement of virtual targets allows organizing the movement of a moving object in complex environments.

Obstacle avoidance method based on unstable driving patterns. Such a bionic approach to circumventing obstacles does not require preliminary mapping, and thus reduces the requirements for the intellectual support of the vessel. The essence of the method is as follows: a bifurcation parameter β is introduced into the structure of the regulator, the value of which depends on the distance to the obstacle. If the distance from the unmanned boat to the obstacle is exceeds the tolerable distance R^*, the bifurcation parameter $\beta = 0$ and the closed-looped system are both in a stable state. In case this distance is less than tolerable R^*, $\beta \neq 0$ and the system becomes unstable. Since this instability is due to the distance to the obstacle, it is natural that the unstable state deviates the vessel from the trajectory on which the obstacle is located in order to increase this distance to the obstacle.

We define the bifurcation parameter in the following form [22]:

$$\beta = \left|R - R^*\right| - \left(R - R^*\right),$$

where R is the distance to the obstacle measured by the sensor, R^* is the allowable distance to the obstacle, i.e. the distance at which it is necessary to begin the procedure of divergence with an obstacle. $|\cdot|$ — modulus of number, i.e. its absolute value.

It is easy to show that if $R \geqslant R^*$, then $\beta = 0$, which means the value of the bifurcation parameter is zero, even if we found an obstacle, but the distance to it is even more acceptable. If $R < R^*$, then $\beta = -2(R - R^*)$. Taking into account that $(R - R^*) < 0$, $\beta > 0$.

As noted, the behavior of the system will be stable if the matrix $G = QT_2$ is positively defined. It follows that in order to bring the system into an unstable mode, one of the diagonal elements of the matrix T_2 must be made negative. We equate it to our bifurcation parameter, i.e. $T_2(1,1) = -\beta$.

The proposed controller operates as follows. The algorithm is executed until the vessel reaches the end point P_k. If an obstacle occurs on the vessel's route, and the obstacle is outside the danger zone, i.e. $R \geqslant R^*$ i.e. $\beta = 0$, then the usual terminal control is calculated by the formula (5). If the condition $R \geqslant R^*$ is not satisfied and $\beta \neq 0$, then the bifurcation parameter is calculated, and the vessel is put into an unstable mode.

Simulation and experiment results

To study the proposed methods, a mathematical model of the surface mini-motorboat "Sigul" was used. The actuators are two propulsion devices based on brushless asynchronous motors and a servo drive shown in fig. 5. Motors and screws are mounted on a movable frame and may deviate from the longitudinal axis by the same angle α (fig. 7). The motors and servo drive are controlled by local regulators, with a PWM signal being applied to their inputs. The inertia of the motors and servo can be neglected compared with the inertia of the object.

To study the synthesized regulator, we will use the following parameters:

— Weight $m = 50$ kg;

— Moments of inertia $J_y = 15.1$ kg / m^2;

— Elements of the matrix of added masses $\lambda_{1,1} = 1.08$ kg, $\lambda_{3,3} = 11.43$ kg, $\lambda_{5,5} = 20$ kg;

—The initial position of the unmanned vessel $P_0 = [0, 0]$;

— Target point $P_k[45, 45]$;

— Terminal control time $T_k = 15$ sec;

— Maximum speed of the boat and moving obstacles $V_{\max} = 2$ m/s;

— The value of the functional matrices in equation (5 $M = \begin{bmatrix} m_x & 0 \\ 0 & m_z \end{bmatrix}$): $R = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix}$, $F'_d = \begin{bmatrix} -c_x V_x^2 \\ -c_z V_z^2 \end{bmatrix}$, $F'_\upsilon = 0$.

Sensors mounted on the vessel mast are three video cameras with a total view field of 135°. The cameras' software allows detecting objects on the water surface at a distance of 50 meters, determining their contours, sizes and distances from a crewless powerboat.

Figures 8, 9 demonstrate the results of the vessel movement modeling. Fig. 8 shows the boat movement of the through the environment with a single stationary obstacle, while fig. 9 displays the boat moving in an environment with two moving obstacles.

As can be seen from the modeling results in the control system, the trajectory of the vessel movement calculations were correct when passing obstacles. In all model experiments, the target point was reached within a set point in time with the boat speed being

Fig. 7. Propulsion and steering complex of the boat

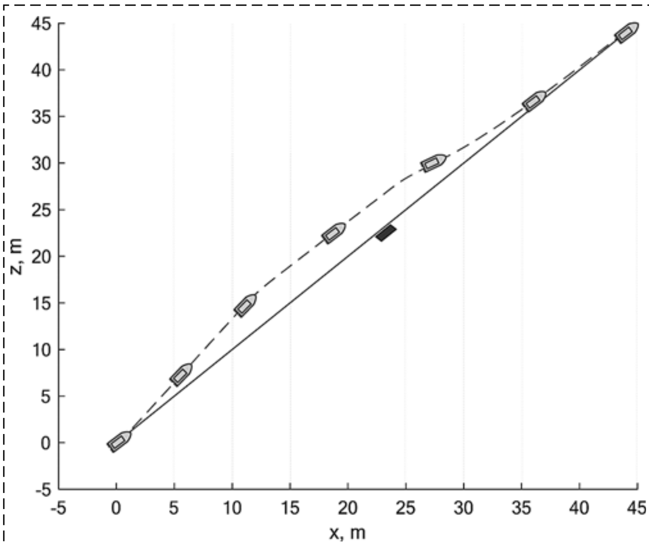

Fig. 8. Trajectory planning with a single stationary obstacle

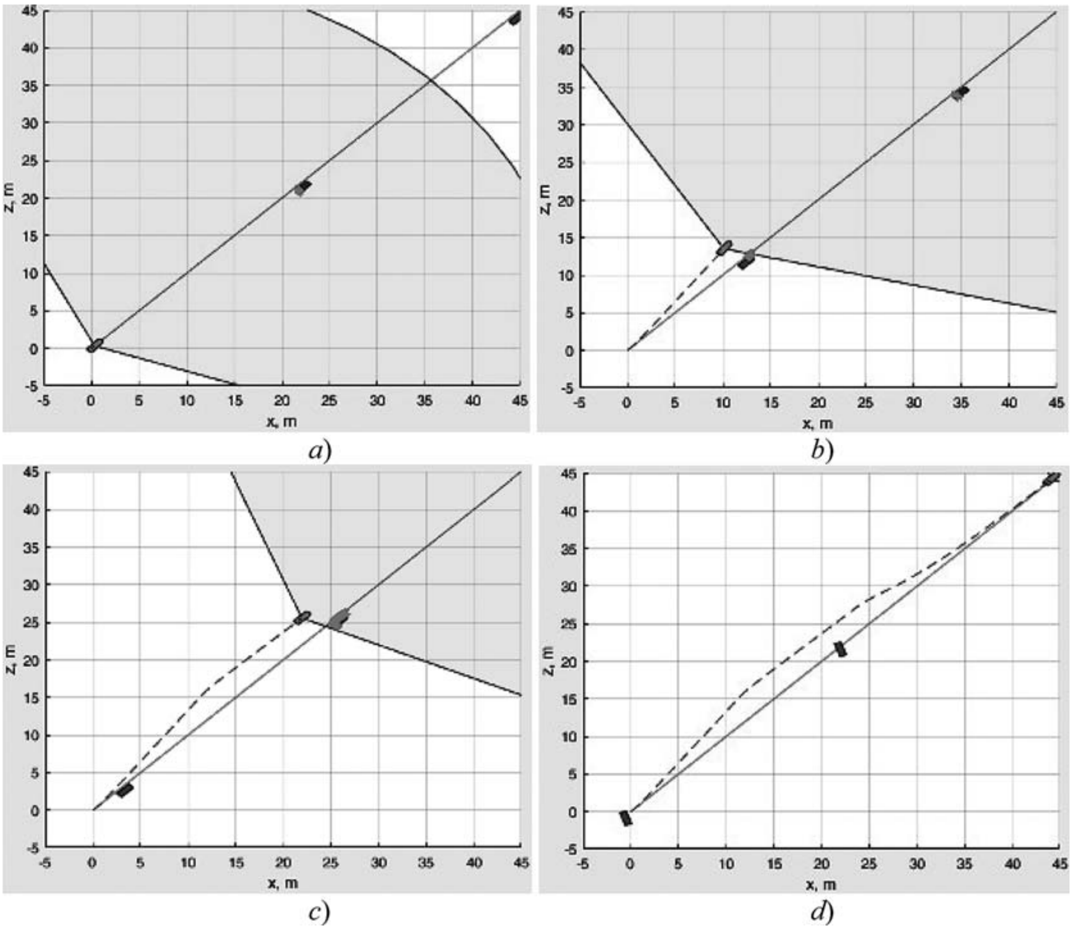

Fig. 9. Trajectory planning with two moving obstacles

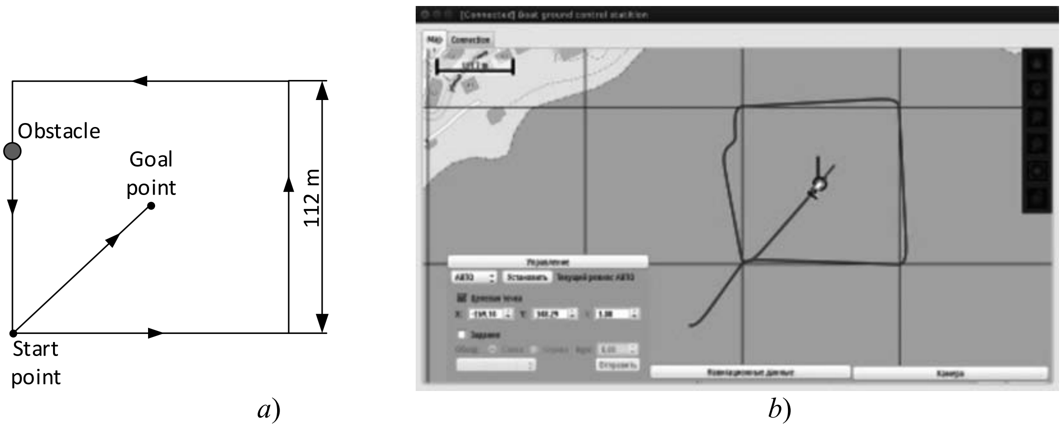

Fig. 10. Experiment results

equal to zero. The range of the repulsive forces of the virtual field corresponded to the range of the boat technical vision system. The minimum distance from the boat to the obstacle was 3 m.

To confirm the effectiveness of the approach, a full-scale experiment was conducted in the Taganrog Bay of the Azov Sea. The boat needed to sail offline on the sides of the square and finish in its center as shown in fig. 10, and in 40 seconds. On one side of the square, an obstacle in the form of a floating buoy was situated. A screenshot from the shore control panel is shown in fig. 10, *b*.

As a result of the experiment, the boat completed the task for a specified time. The minimum distance to the obstacle was 4 m.

Conclusion

The paper presents algorithms for terminal control and scheduling for moving an unmanned boat in an environment with obstacles, based on the position-trajectory algorithm and a hybrid scheduling method based on virtual fields and unstable modes.

The novelty of the proposed approach lies in the method used to develop a local movement trajectory in the field with obstacles and in the hybridization of trajectory scheduling methods. This approach allows us to achieve a given safe distance when avoiding obstacles and virtually eliminate the chances of an emergency collision. The presented results can be used in systems of boats autonomous motion control and allow safe stationary and dynamic obstacles avoidance.

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