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Research Article

Decentralized Control of a Group of Homogeneous Vehicles in Obstructed Environment

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The presented solution is a decentralized control system with a minimal informational interaction between the objects in the group. During control and path planning the obstacles are transformed into repellers by the synthesized controls. The main feature distinguishing the developed approach from the potential fields method is that the vehicle moves in the fields of forces depending not only on the mutual positions of a robot and an obstacle but also on the additional variables allowing solving the problem of robot's path planning using a distributed control system (Pshikhopov and Ali, 2011). Unlike the work by Pshikhopov and Ali, 2011, here an additional dynamic variable is used to introduce stable and unstable states depending on the state variables of the robot and the neighboring objects. The local control system of each vehicle uses only the values of its own speeds and coordinates and those of the neighboring objects. There is no centralized control algorithm. In the local control algorithms the obstacles are represented as vehicles being a part of the group which allows us to unify the control systems for heterogeneous groups. An analysis was performed that proves existence and asymptotic stability of the steady state motion modes. The preformed simulation confirms the synthesis and analysis results.

1. Introduction

In the vast majority of automatic control tasks asymptotic stability of the desired functioning modes is to be achieved. However, there are cases when unstable modes become preferable. For example, an important quality of airplanes is their maneuverability that is achieved by, for example, the fighter parameters approaching the stability boundary or even by crossing it. Another example of an unstable object is a walking robot with its major elements being the unstable pendulums controlled by methods described in numerous publications [1, 2].

The idea of organization of unstable states in the phase space of control systems came up in the works on nonlinear dynamics and synergetics [3, 4], where the notions of attractors and repellers were widely used. A repeller is a mathematical image of a certain object represented as repelling set in the phase space of a controlled object or a system. An attractor is a mathematical image of steady state modes represented as an attractive set in the phase space of an object or a system.

For the first time the idea of using repelling and attracting sets in vehicles control was introduced in the works of Platonov et al. in 1970 [5, 6], where the potentials method was presented as a solution of the path finding problem. In the world literature the main references about using repelling and attracting sets in vehicles control are made to the works of Brooks and Khatib [7–9] published in 1985 and 1986. Another mobile robot control work using the force fields ideas was performed by Hitachi company in 1984 [10]. Nowadays the potential fields method is widely spread. An overview and analysis of methods using potential fields can be found in [11].

Work [8] proposes to summarize the repelling and attracting fields, as well as to represent moving objects by rectangles. Article [12] addresses the problem of the formation of the paths so that no stable equilibrium point exists. Approaches outlined in [8, 12], in general, do not resolve the problem of the mobile robot falling into a local minimum. In [13] an approach that allows bypassing local minima in path formation in an environment with a known map is presented. At the same time this does not consider limitations on movement of robot. In [14] the potential field method is proposed in a form that considers obstacles moving with constant velocity and avoids falling into local minima. In [15] the functions of the repulsive and attractive forces are generated on the plane smashed into cells. These functions are formed such that the stability of path of the mobile robot decreases while its velocity increases. In [16], a function forming a repulsive field and the procedure for calculating its coefficients are proposed. Also work presents conditions under which mobile robot misses the local minima. In [17] the potential field is formed to take into account dynamic constraints of mobile robot and environmental conditions. The moveable object is represented in the phase space. However, [17] did not eliminate the problem of falling into local minima and has a large number of empirically adjustable coefficients. References [18, 19] are devoted to solving the problem of falling into local minima. In [18] the problem is solved on the basis of random changes in the direction of the force and in [19] by the way of describing the obstacles.

Thus, the efforts of many researchers are focused on accounting the dynamics properties of mobile robots and obstacles and eliminating the problem of local minima in the path search problem.

The problem of accounting of the dynamics properties of mobile robots can be solved with the use of the approaches proposed in [11, 20]. In [20] the problem of control of the mobile robot on the plane with obstacles is considered. Repulsive forces are dynamic, they are formed by the introduction of unstable areas in which obstacles are transformed. Unstable mode is set using the bifurcation parameter. The problem of falling into local minima is solved with the use of fuzzy rules or the techniques of target point rotation at an angle proportional to the bifurcation parameter, which itself is a function of the distance to an obstacle. An approach proposed in [20] allows implementing motion along a predetermined path and rapidly changing the trajectory to avoid obstacles using kinematics equations and dynamics of a moving object with the low complexity algorithm.

In [11] approach presented in [20] for the implementation of the path planning and motion control system of mobile robot with sectorial obstacles sensors in the two-dimensional unknown environment was investigated. The results of the simulations are presented.

In [11, 20] unstable modes are used in solution of a problem of motion in obstructed environment where obstacles can form various configurations. The task is to move from an arbitrary point (y_{01}, y_{02}) to the final goal point (y_{f1}, y_{f2}) satisfying the following condition:

$$r_c \geq r, \tag{1}$$

where r_c is distance to the closest obstacle and r is a constant that sets an allowed distance from the vehicle's characteristic point to any of the obstacles Π_j.

Based on the results obtained in [18, 19] we introduce a bifurcation parameter of the following form:

$$\beta = \sum_j |r_c - r| + \sum_j (r_c - r). \tag{2}$$

The parameters of the reference equation of the closed-loop system are formed so that nonzero values of parameter (2) make its roots become positive. Such an algorithm can cause looping motions in environments with complicated obstacles.

In [11, 18] the mentioned drawback is eliminated by direction and angle change in proportion to changes of bifurcation parameter (2):

$$\gamma = k_\gamma \beta. \tag{3}$$

Here we consider the control method using repellers and extend it for the task of vehicle group control.

The main differences of approach proposed at this article are the following:

(a) The method of formation of dynamic repulsive forces, based on the introduction of additional differential equations.

(b) A decentralized control algorithm for a group of robots developed.

(c) Proved existence of asymptotically stable trajectories for robots under dynamic repulsive forces.

2. Problem Statement

As it was mentioned in [18], control method incorporating unstable modes ensures the best effectiveness in the sense of safety (distance to obstacles) during obstacle avoidance and requires the least amount of information for control system's functioning.

The problem of group functioning of autonomous vehicles is one of the major control problems. Here unstable modes can ensure motion with a minimal information exchange and guarantee a maximal safe distance to the obstacles.

Since the path-planning problem is being solved, the following kinematics equations are considered:

$$\begin{aligned} \dot{y}_{1i} &= V_i \cos\varphi_i, \\ \dot{y}_{2i} &= V_i \sin\varphi_i, \end{aligned} \tag{4}$$

where y_{1i}, y_{2i} are vehicle coordinates, V_i is speed, and φ_i is heading, $i = \overline{1,n}$.

Vehicle's position (Figure 1) is described by coordinates y_{1i}, y_{2i} in the external coordinates system Oy_1y_2. Speed V_i and heading φ_i are the control variables. Each object receives information about the position of the neighboring vehicles and coordinates y_L, y_R of the area L where the group is functioning. The number n of vehicles in the group is unknown. The group task is to move along the Oy_2-axis evenly distributing along the Oy_1-axis.

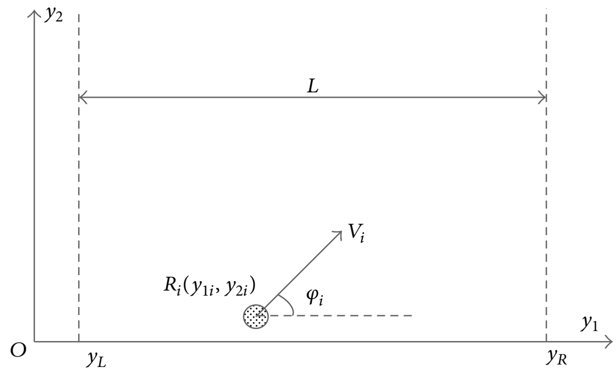


Figure 1: State variables and coordinates system.

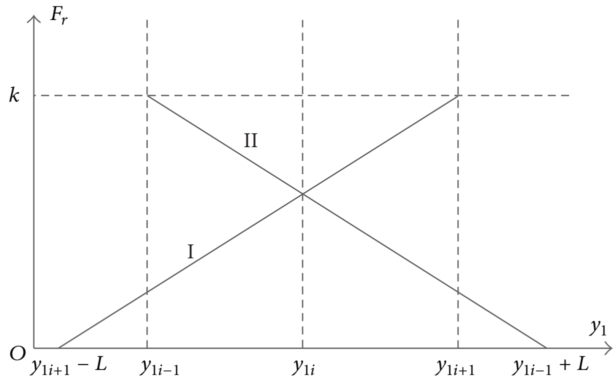


Figure 2: Formation of repellers with linear repelling functions.

3. Group Control Algorithms

Assume $y_{2i} = 0$ and $y_{1i} \neq y_{1j}$, $\forall i \neq i$, $i, j = \overline{1, n}$. Let us enumerate the vehicles so that their index $i = \overline{1, n}$ increases with increasing coordinate y_{1i}. In this case the control algorithm for an ith vehicle can be synthesized in the following way.

Assume that each vehicle is a repeller (repelling manifold) for every neighboring object. In this case interaction of the neighboring vehicles can be described by functions presented in Figure 2. Coordinates y_{1i} are along the abscissa, and the ordinate presents the linear functions for calculation of repellers' attracting forces.

Line I, presented in Figure 2 passing through points $(y_{1i+1} - L, 0)$, (y_{1i+1}, k), is described by the following equation:

$$\frac{y_{1i} - y_{1i+1} + L}{y_{1i+1} - y_{1i+1} + L} = \frac{f_I - 0}{k - 0} \Longrightarrow f_I = \frac{k}{L}\left(y_{1i} - y_{1i+1} + L\right). \quad (5)$$

Likewise, line II passing through points (y_{1i-1}, k), $(y_{1i-1} + L, 0)$ is described by

$$\frac{y_{1i} - y_{1i-1}}{y_{1i-1} + L - y_{1i-1}} = \frac{f_{II} - k}{0 - k} \Longrightarrow f_{II} = \frac{k}{L}\left(-y_{1i} + y_{1i-1} + L\right). \quad (6)$$

Summing the right-hand sides of expressions (5) and (6) we get the equations of additional dynamic variables forming the repellers in the state space of the vehicles group:

$$\dot{z}_i = \frac{k}{L}\left(2y_i - y_{i-1} - y_{i+1}\right). \quad (7)$$

Let us consider the task of stabilization of additional variables z_i and motion of vehicles along the Oy_2-axis with constant speeds. For solution of this task we introduce quadratic functions of the following form:

$$V_i = 0.5z_i^2. \quad (8)$$

The derivative of expression (8) accounting for (7) is

$$\dot{V}_i = z_i \dot{z}_i = \frac{k}{L} z_i \left(2y_{1i} - y_{1i-1} - y_{1i+1}\right). \quad (9)$$

If expression (9) is negatively definite, system (7) is asymptotically stable with respect to the zero state. In order to ensure that function (9) is negatively definite and guarantees constant motion speed the following functional relations are to be satisfied:

$$e_i = \begin{bmatrix} y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2} \\ \dot{y}_{2i} - V_k \end{bmatrix} = 0. \quad (10)$$

The time derivative of the first element of vector (10) accounting for (4), (7) is equal to

$$\dot{e}_i[1] = V_i \cos\varphi_i - \frac{\dot{y}_{1i-1} + \dot{y}_{1i+1} - (k/L)\left(2y_{1i} - y_{1i-1} - y_{1i+1}\right)}{2}. \quad (11)$$

We require the closed-loop system to satisfy the following reference equations:

$$\dot{e}_i[1] + T_{0i} e_i[1] = 0, \qquad e_i[2] = 0, \quad (12)$$

where T_{0i} is constant positive numbers.

Then substituting expressions (10), (11) into (12) yields

$$\begin{bmatrix} u_{ix} \\ u_{iy} \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1i-1} + \dot{y}_{1i+1} - (k/L)\left(2y_{1i} - y_{1i-1} - y_{1i+1}\right)}{2} - T_{0i}\left(y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2}\right) \\ V_k \end{bmatrix}, \quad (13)$$

$$\begin{bmatrix} V_i \\ \varphi_i \end{bmatrix} = \begin{bmatrix} \sqrt{u_{ix}^2 + u_{iy}^2} \\ \arctan\left(\dfrac{u_{iy}}{u_{ix}}\right) \end{bmatrix}. \tag{14}$$

The control algorithm for ith vehicle (13), (14) contains data about its own position y_i and speed V_i, sensory system data about the coordinates y_{i-1}, y_{i+1}, and speeds $\dot{y}_{i-1}$, $\dot{y}_{i+1}$ of the neighboring robots. The speeds $\dot{y}_{i-1}$, $\dot{y}_{i+1}$ and positions y_{i-1}, y_{i+1} of the neighboring vehicles are measured or estimated using the algorithms presented in [21, 22].

Substitution of the expressions (13), (14) into (4), (7) yields the equations of the closed-loop control system:

$$\begin{bmatrix} \dot{y}_{1i} \\ \dot{y}_{2i} \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1i-1} + \dot{y}_{1i+1} - (k/L)(2y_i - y_{i-1} - y_{i+1})}{2} - T_{0i}\left(y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2}\right) \\ V_k \\ \dfrac{k}{L}(2y_{1i} - y_{1i-1} - y_{1i+1}) \end{bmatrix}. \tag{15}$$

From the last expression it follows that the closed-loop system decomposes into two independent subsystems consisting of the first and the third equations and the second equation, respectively. Let us analyze the subsystem consisting of the first and the third equations (15).

In stability analysis it is assumed that variables y_{1i-1}, y_{1i+1} are external measured signals for the control system of ith vehicle. So in stability analysis of ith vehicle we assume $y_{1i-1} = y_{1i+1} = \dot{y}_{1i-1} = \dot{y}_{1i+1} = 0$. Then the first and the third equations of system (15) take the following form:

$$\begin{aligned} \dot{y}_{1i} &= -\left(\frac{k}{L} + T_i\right) y_{1i} - \frac{T_i}{2} z_i, \\ \dot{z}_i &= \frac{2k}{L} y_i. \end{aligned} \tag{16}$$

System (16) is a linear stationary system so we can write its characteristic equation. It has the following form:

$$s^2 + \left(\frac{k}{L} + T_i\right) s + T_i \frac{k}{L} = 0. \tag{17}$$

So the stability conditions of closed-loop system (15) are

$$\begin{aligned} T_i &> 0, \\ k &> 0. \end{aligned} \tag{18}$$

Let us modify the control algorithm (13), (14) introducing an additional component into expression (10):

$$\begin{aligned} e_i &= \begin{bmatrix} y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i - (k_2/L)(2y_{1i} - y_{1i-1} - y_{1i+1})}{2} \\ \dot{y}_{2i} - V_k \end{bmatrix} \\ &= 0. \end{aligned} \tag{19}$$

Then expression (13) transforms into

$$\begin{aligned} &\begin{bmatrix} \left(1 + \dfrac{k_2}{L}\right) u_{ix} \\ u_{iy} \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{(1 + k_2/L)(\dot{y}_{1i-1} + \dot{y}_{1i+1}) - (k/L)(2y_{1i} - y_{1i-1} - y_{1i+1})}{2} - T_i\left(\left(1 + \dfrac{k_2}{L}\right) y_{1i} - \dfrac{(1 + k_2/L)(y_{1i-1} + y_{1i+1}) - z_i}{2}\right) \\ V_k \end{bmatrix}. \end{aligned} \tag{20}$$

And characteristic equation (17) takes the following form:

$$s^2 + \left(\frac{k/L}{1 + k_2/L} + T_i\right) s + T_i \frac{k/L}{1 + k_2/L} = 0. \qquad (21)$$

Algorithm (20) differs from algorithm (13) in the fact that it allows changing both roots of characteristic equation (21) independently of the width of the preset area L and of the value of coefficient k. Stability conditions (18) take the following form:

$$\begin{gathered} T_i > 0, \\ k > 0, \\ k_2 > -\frac{1}{L}. \end{gathered} \qquad (22)$$

In expression (20) the controller parameters are T_i, k_2.

4. Analysis of Group Control Algorithms in Obstructed Environments

Assume that there is one or several stationary obstacles in the environment represented by circles with centers at points (y_1^{pj}, y_2^{pj}). The obstacle size is defined by the radius r_p^j, $j = \overline{1, n_p}$, n_p being number of obstacles.

Let us consider closed-loop system (15). Taking into account that, with conditions (18) satisfied, system (15) is asymptotically stable, we write the equilibrium equations assuming that the derivatives are equal to zero:

$$\begin{aligned} 0 &= -\frac{k}{2L}\left(2y_{1i} - y_{1i-1} - y_{1i+1}\right) \\ &\quad - T_i\left(y_{1i} - \frac{y_{1i-1} + y_{1i+1} - z_i}{2}\right), \\ 0 &= \frac{k}{L}\left(2y_{1i} - y_{1i-1} - y_{1i+1}\right). \end{aligned} \qquad (23)$$

From system (23) we find

$$\begin{gathered} z_i = 0, \\ y_{1i} = \frac{y_{1i-1} + y_{1i+1}}{2}, \\ i = \overline{1, n}. \end{gathered} \qquad (24)$$

Accounting that $y_0 = y_L$, $y_{n+1} = y_R$, solution (24) can be written as

$$\begin{aligned} y_n &= \frac{y_L + ny_R}{n+1}, \\ y_i &= \frac{y_L}{i+1} + \frac{iy_{1i+1}}{i+1}, \quad i = \overline{n-1, 1}. \end{aligned} \qquad (25)$$

Expression (25) gives the distance to the neighboring vehicles in steady state mode:

$$y_{1i} - y_{1i-1} = \frac{1}{n+1} y_R = \frac{L}{n+1}. \qquad (26)$$

The idea of applying the approach presented in the previous section to the environments with stationary obstacles is that they are being formally treated as vehicles. In this case the distributed control system for a group of robots (15) will successfully function if the following condition is satisfied:

$$r_p^j < \frac{L}{n + n_p + 1}, \qquad (27)$$

where r_p^j is obstacle radius.

In the presence of obstacles the lengths of vehicle's paths can essentially differ. So there is a task of keeping the motion line by all the vehicles. In order to solve this task the following strategy is introduced. The leftmost vehicle is selected to be a leader and performs motion with a constant speed V_k. The rest of the vehicles keep the same strategy of distribution along the Oy_1-axis but receive the coordinate y_2 of the next left vehicle as a setting value.

In the obstructed environment we must control both coordinates. So let us introduce the following error vector:

$$\begin{aligned} e_1 &= \begin{bmatrix} y_{11} - \dfrac{y_L + y_{12} - z_1}{2} \\ \dot{y}_{21} - V_k \end{bmatrix}, \\ e_i &= \begin{bmatrix} y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2} \\ y_{2i} - y_{2i-1} \end{bmatrix}, \quad i = \overline{2, n}. \end{aligned} \qquad (28)$$

Then the local control algorithms take the following form:

$$\begin{bmatrix} u_{1x} \\ u_{1y} \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1L} + \dot{y}_{12} - \dot{z}_1}{2} - T_{11}\left(y_{11} - \dfrac{y_{1L} + y_{12} - z_1}{2}\right) \\ V_k \end{bmatrix}, \qquad (29)$$

$$\begin{bmatrix} u_{ix} \\ u_{iy} \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1i-1} + \dot{y}_{1i+1} - \dot{z}_i}{2} - T_{1i}\left(y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2}\right) \\ \dot{y}_{2i-1} - T_{2i}\left(y_{2i} - y_{2i-1}\right). \end{bmatrix}. \qquad (30)$$

As before, in expressions (29), (30) it is assumed that the speeds of the neighboring objects are measured or estimated. The laws of changing speeds and orientation angles are determined by expression (14).

Then the equations of the closed-loop system take the following form:

$$\begin{bmatrix} \dot{y}_{11} \\ \dot{y}_{21} \\ \dot{z}_1 \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1L} + \dot{y}_{12} - \dot{z}_1}{2} - T_{11}\left(y_{11} - \dfrac{y_{1L} + y_{12} - z_1}{2}\right) \\ V_k \\ \dfrac{k}{L}\left(2y_{11} - y_{1L} - y_{12}\right) \end{bmatrix}, \quad (31)$$

$$\begin{bmatrix} \dot{y}_{1i} \\ \dot{y}_{2i} \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1i-1} + \dot{y}_{1i+1} - \dot{z}_i}{2} - T_{1i}\left(y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2}\right) \\ \dot{y}_{2i-1} - T_{2i}\left(y_{2i} - y_{2i-1}\right) \\ \dfrac{k}{L}\left(2y_{1i} - y_{1i-1} - y_{1i+1}\right). \end{bmatrix}. \quad (32)$$

From system (31), (32) it follows that steady state for the variables z_i and y_{1i} is described by the expressions (24) and the stability conditions have the form of (18).

For the steady state analysis of the variables y_{2i} we write the second equations of (31), (32):

$$\begin{aligned} \dot{y}_{21} &= V_k, \\ \dot{y}_{22} &= \dot{y}_{21} - T_2\left(y_{22} - y_{21}\right) = V_k - T_2\left(y_{22} - y_{21}\right), \\ \dot{y}_{23} &= \dot{y}_{22} - T_2\left(y_{23} - y_{22}\right) = V_k - T_2\left(y_{22} - y_{21}\right) \\ &\quad - T_2\left(y_{23} - y_{22}\right) = V_k - T_2\left(y_{23} - y_{21}\right), \\ &\vdots \\ \dot{y}_{2i} &= V_k - T_2\left(y_{2i} - y_{21}\right), \\ &\vdots \end{aligned} \quad (33)$$

Integrating the first equation in (33)

$$y_{21} = y_{21}^0 + V_k t. \quad (34)$$

Then accounting for (34) the last equation in (33) takes the following form:

$$\dot{y}_{2i} + T_2 y_{2i} = V_k + T_2\left(y_{21}^0 + V_k t\right). \quad (35)$$

Solving (35) yields

$$y_{2i}(t) = \left(y_{2i}^0 - y_{21}^0\right) e^{-T_2 t} + y_{21}^0 + V_k t, \quad (36)$$

where y_{21}^0, y_{2i}^0 are initial positions of the vehicles.

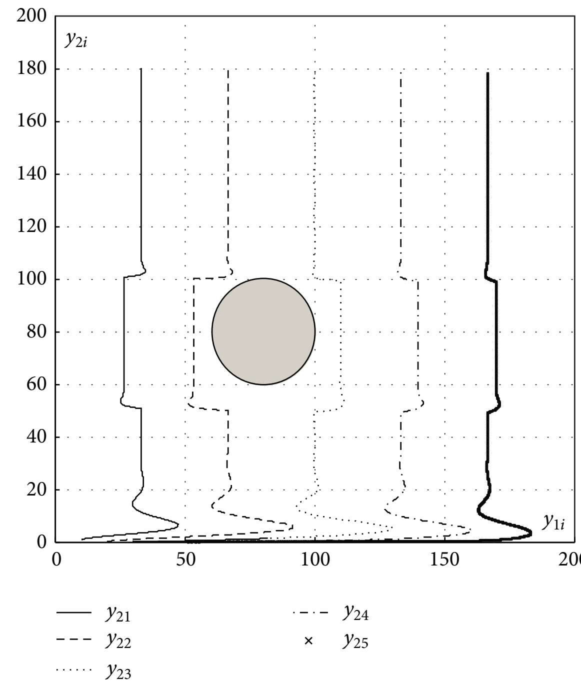


Figure 3: Modeling results for control systems (4), (7), (14), (29), and (30) with a stationary obstacle.

From expression (36) it follows that

$$\lim_{t\to\infty} y_{2i}(t) = \lim_{t\to\infty}\left(\left(y_{2i}^0 - y_{21}^0\right) e^{-T_2 t} + y_{21}^0 + V_k t\right) = y_{21}^0 + V_k t. \quad (37)$$

Comparing (34) and (37) we see that after a time positions of all the vehicles along the Oy_2-axis approach the position of the leftmost vehicle. So the group keeps the line.

Control algorithms (29), (30) are added with the following logical conditions.

If ith vehicle in the group detects an obstacle to its left, its number increases by one and the control algorithm (30) takes the following form:

$$\begin{bmatrix} u_{ix} \\ u_{iy} \end{bmatrix} = \begin{bmatrix} \dfrac{\dot{y}_{1i-1} + \dot{y}_{1i+1} - \dot{z}_i}{2} - T_{1i}\left(y_{1i} - \dfrac{y_{1i-1} + y_{1i+1} - z_i}{2}\right) \\ \dot{y}_{2i-2} - T_{2i}\left(y_{2i} - y_{2i-2}\right). \end{bmatrix}, \quad (38)$$

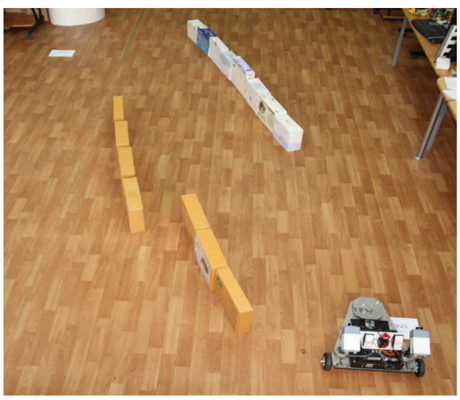
If ith vehicle in the group detects an obstacle to its right, control algorithm (30) remains unchanged.

For the leftmost and rightmost vehicles the control algorithms remain unchanged in case of obstacle detection.

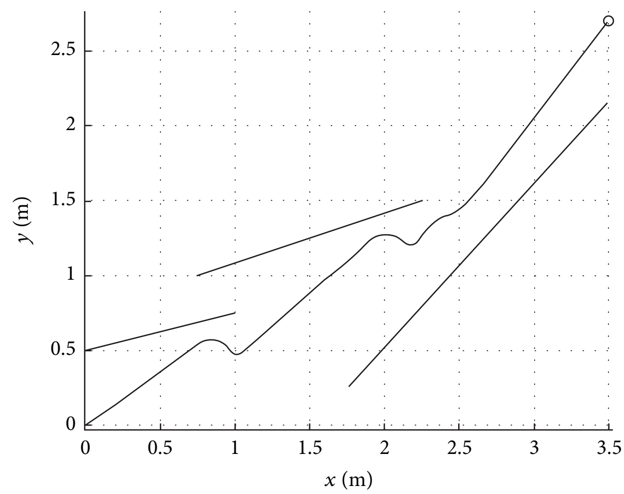
5. Modeling Results

The vehicle's model is described by (4) and control law by expressions (7), (14), (29), and (30).

FIGURE 4: Autonomous mobile robot "Skif 3."



General scene view with a group of linear obstacles



Motion trajectory

FIGURE 5: Experimental results.

The control system's parameters: working area $L = 200$ m, $y_L = 0$ m, $y_R = 200$ m; number of vehicles $n = 5$; setpoints for speed $V_{0i} = 1$ m/s; time constants $T_{0i} = 1\,s^{-1}$; initial conditions $y_{2i} = 0$, $y_{11} = 10$, $y_{12} = 20$, $y_{13} = 30$, $y_{14} = 40$, $y_{15} = 50$ m; center coordinates and obstacle are radius (80, 60) and 20 m.

For the safety reasons the vehicle maneuvers start at the distance of 10 meters to an obstacle. The maneuver is started by a vehicle closest to the detected obstacle.

Figure 3 presents the modeling results for the control algorithms described by expressions (29), (30).

Figure 3 shows that a group of vehicles distributes itself evenly across the area. As the second and third vehicles approach the obstacle at the distance less than 10 m, they start to treat the detected obstacle as another vehicle. As a result, the group splits itself into two subgroups. The first subgroup passes the obstacle to its left, while the second one passes it to its right. After the obstacle is passed, the vehicles regroup into the initial configuration and continue their motion.

From Figure 3 we see that the distributed control system not only performs an even distribution of the vehicles along the Oy_1-axis but also ensures keeping of the line.

6. Experiment Results

The experiment was held using autonomous wheeled robot "Skif-3," developed in Department of Electrical Engineering and Mechatronics of Taganrog Institute of Technology of Southern Federal University. Robot is shown in Figure 4.

Algorithm (10) was implemented using Advantech onboard computer. Distance to obstacles is measured by stereo vision using two cameras. Current coordinates of robot are determined by integrating kinematic equations (18). It should be noted that in real control systems more simple sensors could be used for obstacles distance measurement.

Experiments results are shown in Figure 5.

Experimental results shown in unknown environment demonstrate efficiency of approach proposed in this paper.

7. Conclusion

The article presents and analyzes the algorithms of distributed control for a group of vehicles using a control principle based on interpretation of all the neighboring objects as repellers. The proposed methods of repellers' introduction are outstanding in the sense of dynamic way of generation of repelling forces utilizing unstable modes. Note that the graphs presented in Figure 2 are not the images of repelling forces formed as a result of integration of the mentioned lines.

The performed analysis and modeling results demonstrate effectiveness of the proposed methods for the obstructed environments. The proposed approach can also be applied for nonstationary environments because the obstacles are formally treated as vehicles.

The proposed algorithms can be used in the path-planning systems of various vehicles. The planned path ensures motion stability at the level of object's kinematics. Implementation of the planned paths requires an additional controller accounting for the equations of dynamics and its actuators [23].

Using the vehicle's equations of kinematics and dynamics of the proposed approach allows us to join the levels of planning and motion control. It is possible to form repellers as functions of positions, speeds, and accelerations of the vehicles.

Competing Interests

The authors declare that they have no competing interests.

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