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THE PLANNER OF MOVEMENT OF A QUADROCOPTER BASED ON VORONOI DIAGRAM

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ABSTRACT

The purpose of work is the solution of a problem of planning of movement of a quadrocopter in the environment with an unknown obstacles location. The solution of a task is carried out using the Voronoi diagram. The analysis of many known works showed that planning of movement of movable object in the environment with an unknown location of obstacles requires large computing resources. In article the algorithm of mapping of the environment based on information of locator is offered. The locator is mounted on a movable object. The task of planning of a trajectory is solved in real time. The stages of algorithm of a clustering of coordinates of the obstacles are defined. The version of the analysis of clusters of coordinates through crossing of polygons is offered. A procedure for the analysis of sensor data at the coincidence of the information with the data in the base of coordinates. The modes of the movement of movable object in the environment are considered: the movement between obstacle, the movement from the left and from the right from obstacles, the movement without obstacles. The description of the bypass mechanism of obstacles in an increment of coordinates of the extreme points belonging to one object is provided. The movement between obstacles on an edge of Voronoi diagram is considered, that corresponds to the case of an incomplete road map. The modeling of the movement in case of location of obstacle near the aim and at a uniform location of obstacles in the environment is carried out.

Keywords: planning of a trajectory, Voronoi diagram, mapping environment, quadrocopter.

INTRODUCTION

The methods of planning of trajectories of autonomous movable objects can be divided into intellectual and graphic-analytical. Intellectual methods include methods based on neural network approach and fuzzy logic [1 - 4]. The graphic-analytical methods include method of potential fields, methods using Voronoi diagrams, methods based on the inertial properties of a movable object [5 - 7]. The research of graphic-analytical methods is an actual task. Graphic-analytical methods are the basis for the development of more complex combined methods. The combination of methods allows to expand possibilities of known graphic-analytical methods and to plan safe movement of movable object in environments with a priori unknown location of obstacles.

Voronoi diagram is used recently for solving of a problem of planning of a trajectory in an environment with a priori uncertainty. This can be explained from the fact that implementation of algorithms requires a lot of time and computing resources because of large volume of geometrical calculations. The algorithm of mapping of the environment offered in article differs in possibility of reduction of computing loading at the planning a trajectory of movable object in the environment with a priori unknown location of obstacles using Voronoi diagram.

During planning of a trajectory of a quadrocopter its movement in the environment with obstacles from a point A (x_0, y_0, z_0) and in B (x_1, y_1, z_1) point is considered. A priori information about the location of obstacles is not available. The system of technical vision of movable object is locator. An angle of disclosure of diagram of a locator from -45° to +45° from a longitudinal axis of movable object, and the range – 2,5m. Traffic control is implemented with use of the position regulator of movement.

The researches of the developed method are carried out by modeling of work of the planner of movement of movable object together with the position regulator of movement in MATLAB.

THE ANALYSIS OF KNOWN SOLUTIONS OF APPLICATION OF VOROMOI DIAGRAMS FOR PLANNING OF TRAJECTORIES

A Voronoi diagram is a partition the plane with n points (centers) on a set of convex polyhedrons (cells). Each polyhedron contains one center. Any point in this polyhedron is closer to its center than to any other center.

Classical geometrical approaches to creation of trajectories [8] can be divided into two main groups: method of partition into cells [9], method of a roadmap [10].

Not crossed cells at the description of free for the movement space, are used in a method of partition into cells. The partitioning can be exact and approximate. At approximate partition the space is parted until each cell doesn't appear completely in free space or completely inside an obstacle. Process of recursive division is stopped on reaching the set accuracy. Exact partition into cells works faster than approximate, but the received trajectories have big length.

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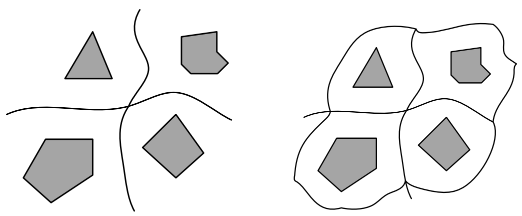
In a method of a roadmap [10] the graphs for description of connectivity free space for movement are used. This method has several options, but the most distributed is the probabilistic method of a roadmap [11]. The methods of a roadmap based on the graph of visibility for search of the shortest way and the Voronoi diagrams for the most freeway are applied. It should be noted that the Voronoi diagram is built for $O(n\log n)$ of steps of modeling at n network nodes, and creation of the graph of visibility will take no more $O(n^2)$ of steps on the same map.

The specified defect can be eliminated using the methods of smoothing of a trajectory [12]. In [6], the authors combined the Voronoi diagram, graph visibility and potential field method. This combining allows reaching a compromise between indicators of the safest and shortest trajectory. As a result it is possible to receive shorter way, than the way defined only on the basis of the Voronoi diagram. The received shorter way may be not optimal.

The creation of the Voronoi diagram on a set of polygons is a difficult and expensive on time process. In work [13] approximation of an obstacle in the form of polygons by points on their edges is offered and diagrams on these points are constructed. The edges which crossed obstacles were removed. At first the Delaunay triangulation [14] was created, and then on it the Voronoi diagram for $O(n)$ steps is constructed.

In work [13] it is offered to generate after creation of a triangulation Delaunay a roadmap with addition in a triangulation of an initial and target point. The roadmap is generated by removal of those edges of the Voronoi diagram, which are from obstacles less than on the doubled safety radius ($2C_{min}$). If at creation of the Voronoi diagram to use only points of obstacles, the received roadmap will be incomplete. In Figure-1 an incomplete (Figure-1a) and complete (Figure-1b) roadmaps are shown. The task of getting a complete roadmap is solved as follows.

The frame covering obstacle tops is created. Then the frame is extended not less, than on $2C_{min}$ in all directions. Then the Voronoi diagram on the points approximating obstacles and on a surrounding framework is created. On the basis of a Voronoi diagram the complete roadmap is obtained, an example of which is shown in Figure-1b.



a *b*

Figure-1. Incomplete and complete roadmaps.

The shortest way on the obtained complete roadmap may significantly differ from the optimal way because of the shape of obstacles. To solve this problem the approximating points of the describing framework are pulled together to the nearest point of an obstacle on distance not less $2C_{min}$ [13].

The Voronoi diagram is created on the approximating points of an obstacle and points on a tightened framework. If necessary new initial and target points are set, the previous initial and target points are removed from a triangulation dynamically.

For reduction of length of the shortest way on a roadmap in work [13] simple approach is offered. For v v_i top on the way ($i=\{1,\dots,n-2\}$) is checked, has a segment $\overline{v_i v_{i+2}}$ a distance to the next obstacle less or equal C_{min}. If the condition is carried out, the top v_i+1 is removed from the shortest way and process of search is continued. After completion of process of reduction of length of a way the procedure of smoothing of a trajectory using Steiner's points is made [15].

The offered method allows to receive a trajectory, optimal from the point of view of safety and length. This method has low computing efficiency because of existence of several iterative algorithms. Also there are no requirements to a C_{min} parameter choice.

In work [16] the algorithm of expansion of borders for creation of the Voronoi diagram is used. This work is directed on research of a district map, but not on movement to a target point, but its some approaches can be used for successful bypass of obstacles. There are approaches modifying the Voronoi diagram, in particular, a method of planning of a trajectory of the mobile robot in the unknown environment on the basis of the generalized Voronoi graph [17-19].

THE ALGORITHM OF MAPPING OF AN ENVIRONMENT

Data coming from the locator does not allow to create the Voronoi diagram without attraction large volumes of computing. At each stage of the movement of movable object the set of coordinates are come from a locator.

Without reliable data processing the belonging of coordinates to different obstacles cannot be estimated and their location relative to a movable object.

For effective planning of the movement in the conditions of uncertainty it is necessary to do mapping of the district at one speed with process of movement of movable object. Of course, it is possible to store all data from a locator, and then to carry out full search of coordinates for the analysis of belonging of points to different obstacles.

However, at accumulation of information it is necessary to operate with large volumes of data. Such decision doesn't allow meeting the requirements of

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simultaneous mapping and the organization of movement of movable object.

The essence of the offered process of mapping is shown in Figure-2.

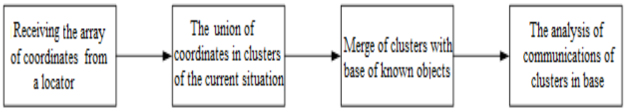

Figure-2. Explanation of the mapping process.

Mapping is carried out in few stages.

Stage 1. Retrieving data from a locator in form of an array of intensities rays reflected from obstacles.

Stage 2. The union of coordinates in clusters by the analysis of distances between points in procedure of full search and parallel elimination of redundancy, and also by removal of coordinates of points with norm $\|r\|<\delta$ the neighboring points (see Figure-3). δ parameter is selected based on the dimensions quadrocopters.

As a result an array of cells with coordinates of the objects which are in sight of movable object is obtained.

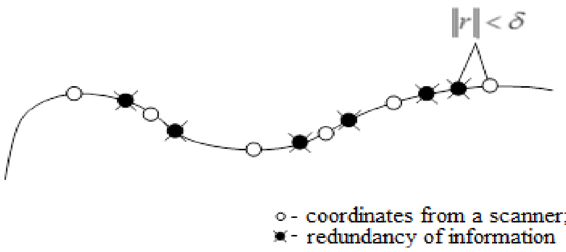

Figure-3. Elimination of redundancy of information.

Stage 3. The union of an array of cells with coordinates of objects in a quadrocopter sight with the base of cells containing coordinates of all known objects at the current time.

Stage 4. The analysis of communications for merge of clusters of the coordinates belonging to one or different objects which does not allow to execute safe movement of a quadrocopter between them.

In Figure-4 combination of information from a locator with already available information in base of cells of coordinates of all known objects is shown.

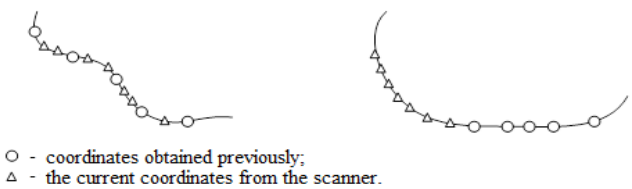

Figure-4. Possible options for the mutual arrangement of new and known coordinates of the object.

On Figure-4(a) the coordinates of points of a locator belonging to the same object are crossed with existing coordinates in base. In Figure-4(b) the new and known coordinates of points belonging to the same object aren't crossed. The stage 4 is carried out in two stages for reduction of computing operations. In the first case (see. Figure-4(a)) for combination of information the polygon for each object is created from the full array of cells and their pairwise intersection is looked for. The search is carried out using the algorithm of Weiler-Atherton [20-21], or the algorithm of Bentley-Ottmann [22-23].

If couple of polygons has at least one general point, two clusters of coordinates are combined. In the second case (see. Figure-4(b)) for combination of information in the array of coordinates data are located from left to right. Such location of data is associated with feature of representation of the information by locator. In the array of cells with coordinates of the current situation the coordinates of each object are located from left to right. Consequently, it is enough to compare norms of distances between extreme coordinates in each couple of clusters and to define the identity to one or different objects that is shown in Figure-5.

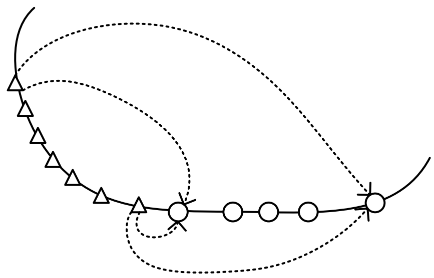

Figure-5. The analysis of clusters of the coordinates belonging to one object.

When the fourth stage is carried out the base of clusters of coordinates of objects is obtained. The elimination of full search of coordinates in a large array of data makes the offered algorithm computationally effective and allows to use it in real time at planning the movement of movable object.

ALGORITHM OF PLANNING BASED ON VORONOI DIAGRAM

Let's consider some of the modes of movement of the movable object in the environment with obstacles, shown in Figure-6.

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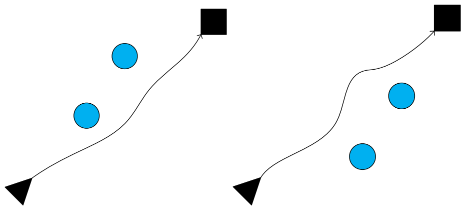
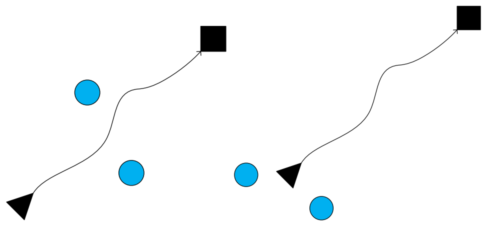


a - movement from the right of obstacles b - movement from the left of obstacles



c - movement between the obstacles d - movement without obstacles

Figure-6. The movement modes in the environment with obstacles.

If there are no any obstacles in sight of movable object, the movement mode without obstacles is carried out. The movement to the target can be organized by setting for the target of the attracting potential, as in a method of potential fields [5]. Let's consider the organization of the modes of the movement to the right or left of the obstacles. After definition of the next obstacle to quadrocopter, the extreme point of an obstacle is chosen. The movement to the left of an obstacle is shown in Figure-7.

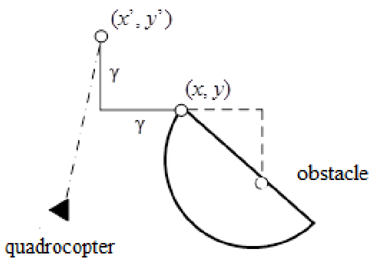


Figure-7. Movement from the left of obstacles.

At bypass of *i-th* obstacle at the left, the coordinates (x, y) of first point from *i-th* cluster are chosen. At bypass of an obstacle at the right, the coordinates of last point are chosen. The increment of coordinates is set $(x+\gamma, y-\gamma)$ and $(x-\gamma, y+\gamma)$ (where γ - a safety indicator). From the two obtained points the most remote point from an obstacle (x', y') is chosen and the movable object goes to it. Thus, the safe bypass of an obstacle is provided.

In Figure-8 the movement mode between obstacles in the form of sequence of K-1, K, K+1 steps is shown. The movement in this mode consists of sequence of three stages.

Stage 1. Search of coordinates of the next points (x_1, y_1), (x_2, y_2) of obstacles to movable object.

Stage 2. Stage-1. Search of coordinates (x_0, y_0) of the middle of segment, connecting the next points.

Stage 3. The movement to (x_0, y_0) point.

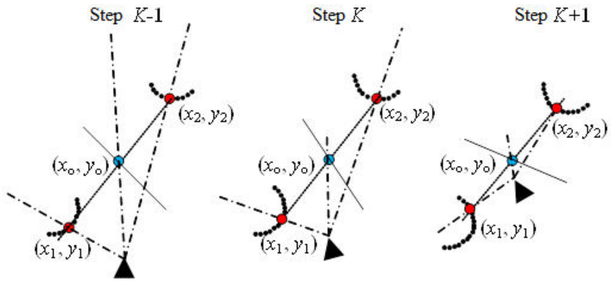


Figure-8. Movement between obstacles.

The movable object moves in the conditions of aprioristic uncertainty. On each step the point (x_0, y_0) belongs to the general edge of two polygons of the Voronoi diagram, containing each of obstacles. It corresponds to the case of an incomplete roadmap. To improve the smoothness of the trajectory in this mode can be organized the movement of movable object on an arc of circle.

MATHEMATICAL MODEL OF A QUADROCOPTER

The mathematical model of a quadrocopter is a combined system of the equations in which linear sizes are expressed in fixed coordinate system, and angular - in moving coordinates [24]:

$$\begin{cases} \ddot{x} = (s_\psi s_\varphi + c_\psi s_\theta c_\varphi)\dfrac{U_1}{m}, \\ \ddot{y} = (-c_\psi s_\varphi + s_\psi s_\theta c_\varphi)\dfrac{U_1}{m}, \\ \ddot{z} = -g + c_\theta c_\varphi \dfrac{U_1}{m}, \\ \dot{p} = \dfrac{I_{yy} - I_{zz}}{I_{xx}} qr - \dfrac{J_{TP}}{I_{xx}} q\Omega + \dfrac{U_2}{I_{xx}}, \\ \dot{q} = \dfrac{I_{zz} - I_{xx}}{I_{yy}} pr + \dfrac{J_{TP}}{I_{yy}} p\Omega + \dfrac{U_3}{I_{yy}}, \\ \dot{r} = \dfrac{I_{xx} - I_{yy}}{I_{zz}} pq + \dfrac{U_4}{I_{zz}} \end{cases} \tag{1}$$

where x, y, z - center of gravity position of a quadrocopter in an inertial reference system; $s_\theta, s_\phi, s_\psi, c_\theta, c_\phi, c_\psi$ - the sines and cosines of the angles of orientation of a quadrocopter (ϕ - angle of bank

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(rotation around axis *X*); θ - pitch angle (rotation around axis *Y*); ψ - yaw angle (rotation around axis *Z*)); *m* – mass of the aircraft; *g* - acceleration of gravity; *p, q, r* – angular speeds of rotations of a quadrocopter round axes of coordinates; *I* - the moments of inertia about the respective axes; *J* - the moment of inertia of an engine with a propeller reduced to the rotor axis; U_i - forces and the moments proportional to squares of speeds of rotation of propellers described by the following expression:

$$U = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ bl(\Omega_4^2 - \Omega_2^2) \\ bl(\Omega_3^2 - \Omega_1^2) \\ d(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2) \end{bmatrix} \quad (2)$$

where l - distance between the center of a quadrocopter and the center of the propeller; b, d - v; $\Omega = [\Omega_1 \quad \Omega_2 \quad \Omega_3 \quad \Omega_4]^T$ - a vector of speeds of rotation of propellers.

POSITION REGULATOR OF MOVEMENT

The movement regulator based on PD-law was developed for research of a method of planning of a trajectory.

The output of the regulator is the vector of speeds of rotation of each engine. This vector is calculated taking into account that pair of engines 1-3 creates movement along axis 0X, and couple 2-4 - along axis 0Z. An yaw angle during the movement is remained unchangeable.

The resultant vector of desirable speeds of rotation of propellers is calculated on the following formula:

$$w_c = \left[w_{yc} - w_{xc} / 2 \quad w_{yc} - w_{zc} / 2 \quad w_{yc} + w_{xc} / 2 \quad w_{yc} + w_{zc} \right] \quad (3)$$

The components of an expression (4) are calculated as follows:

$$w_{xc}(i+1) = k_{p1}(V_{x з}(i) - V_x(i)) + k_{d1}((V_{x з}(i) - V_x(i)) - (V_{x з}(i) - V_x(i-1)))/T$$

$$w_{yc}(i+1) = \sqrt{g/4b} + k_{p2}(y_з(i) - y(i)) + k_{d2}((y_з(i) - y(i)) - (y_з(i) - y(i-1)))/T \quad (4)$$

$$w_{zc}(i+1) = k_{p3}(V_{z з}(i) - V_z(i)) + k_{d3}((V_{z з}(i) - V_z(i)) - (V_{z з}(i) - V_z(i-1)))/T$$

where *i* - number of a step of calculation of the control action; k_{pj}, k_{dj}, j = 1, 2, 3 - the coefficients of the proportional and differentiating components; $V_{x з}$, $V_{z з}$ - the projections of desirable speed of movement calculated by the regulator; V_x, V_z - the projections of speed of movement; g - acceleration of gravity, $y_з$ - the set height of flight, T - sampling step.

During the movement on a trajectory the regulator calculates the projections of desirable speed of movement on the following formula:

$$V_з = [V_{\max}\cos(\varphi) \quad 0 \quad V_{\max}\sin(\varphi)] \quad (5)$$

where φ - the angle between the current and planned coordinates of a quadrocopter in the plane 0XY; $V_{\max}$ - the maximum speed of the quadrocopter.

During the braking in the vicinity of a target point the projection $V_{зx}$ of desirable speed is defined according to the following expression:

$$V_{зx} = \frac{V_{\max} \cdot \cos(\varphi) \cdot \mathrm{sgn}(x_з - x)}{1 + e^{-a|x-b|}} \quad (6)$$

where *a*, *b* - parameters that define the shape of the exponential function.

The expression for $V_{зz}$ has a similar form.

RESEARCH OF THE PLANNER OF MOVEMENT OF MOVABLE OBJECT

The developed algorithm is programmed in a MATLAB package. The model of a quadrocopter with the following parameters was used: $J_{TP} = 73{,}9 \cdot 10^{-6}$ kgm^2; $m = 1$ kg; $I_{XX} = I_{YY} = 0{,}081$ kgm^2; $I_{ZZ} = 0{,}142$ kgm^2; $l = 0{,}24$ m; $b = 53{,}81 \cdot 10^{-6}$ Ns^2/rad^2; $d = 1{,}1 \cdot 10^{-6}$ Nms^2/rad^2, V_{max}=2,5m/s.

The modeling was carried out with a step of sampling T = 0, 01c. At the initial time quadrocopter was in the position (0, 0, 0), then rose to the point (0, 1, 0) and after that moved to the target point (10, 1, 10). The indicator of safety was accepted equal γ = 0, 5m.

The obstacles were represented by circles with radiuses 0,5m and 1m. The results of modeling are shown in Figure-9.

The following modeling was implemented:

- the movement mode between obstacles (Figure-9a);
- the movement mode to the left of obstacles (Figure-9b);
- the movement mode to the right of obstacles (Figure-9c);
- an obstacle is near the target (Figure-9d);
- the evenly located obstacles (Figure-9e).

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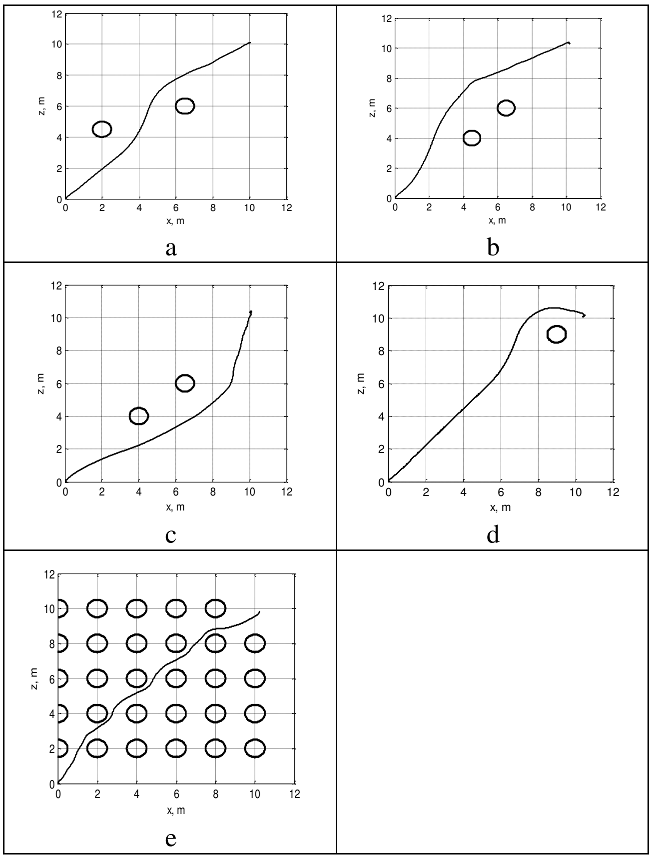

Figure-9. The results of modeling of movement of a quadrocopter.

The analysis of results of modeling shows the following. Lack of mapping of the environment and existence in the environment of several obstacles doesn't allow planning the movement of movable object in real time because of big computing operations. Preliminary mapping of the environment significantly increases efficiency as it is carried out with planning process. All main modes of the movement of movable object were successfully implemented.

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CONCLUSIONS

The analysis of the received results shows that, unlike results of works [10, 13, 15], the mapping of environment in order to reduce the uncertainty the planner of movement of movable object with application of Voronoi diagram with small amount of computing operations allows to implement. The algorithm of mapping is carried out along with process of planning and can be successfully used for solution of problems of research of the environment. The developed algorithm of planning of movement of a quadrocopter using the Voronoi diagram provides high safety and speed of movement. The received results show the efficiency of the offered algorithm for the solution of a problem of safe movement of movable object in the environment with obstacles.

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