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Modeling the Detection of Moving Objects by Means of a Spatially Distributed Continuous Monitoring System with a Dynamic Structure

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Abstract: The class of monitoring systems, which is equipped with mobile means of detection, is considered. Unmanned aerial vehicles are used as detection means. The area of responsibility of the system is a geographic space with counteraction for both detection equipment and objects of observation. An original approach to the development of a simulation model for detecting moving objects of observation in the area of a spatially distributed continuous monitoring system with a structure is proposed. The movement of sensors is displayed along trajectories, which are Hamiltonian cycles on the terrain graph. The new approach is to use the approach used to ensure the flexibility of the resulting solutions to the problem of monitoring space and the ability to respond quickly to various factors and other conditions of use based on self-organizing mechanisms. At the same time, both the system itself, designed to solve the tasks of continuous monitoring and the solutions found for specific monitoring tasks and spatially distributed systems, provide continuous monitoring and are resistant to destructive influences of various kinds.

The constructed simulation model and the experiments performed using the principles of dynamic detection of detection means in the area of a spatially distributed continuous monitoring system. At each moment of time, the optimal configuration of the parameters is determined, which is used as the most effective solution of the problem from the point of time of detecting an object in the monitoring area of vision. The model does not depend on the type of sensors used in the network and the implementation of the ideological principles embodied in the concept of dynamic systems. Based on the results of the experiments carried out, conclusions are drawn about the characteristics of continuous monitoring, which provides a basis for further work to optimize these indicators.

Keywords: continuous monitoring system, unmanned aerial vehicle, spatially distributed system, monitoring object, mobile detection facility, Hamiltonian cycle

1. INTRODUCTION

Temporarily distributed continuous monitoring systems demonstrate modern service and support functions of the airborne dynamic detection system, which ensure the solution of problems of maintaining the space-probabilistic-temporal functions (SPTF) at the required level [1,2]. SPTF related to monitoring of the probability of detecting objects in a given period of time.

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The main tasks of the systemic continuous monitoring of the class are prompt and high-precision detection of objects, their further support and timely delivery of the object to the end user [3,4].

The classical approach to solving the problem of monitoring the space of continuous observation over the maximum possible monitoring area. Often this problem is solved using stationary systems that are not distributed in nature [5, 6]. The problems of a negative character are presented when solving a general character. To provide more flexibility, network monitoring systems are used [7-10].

However, more attentively, approaches to the organization of the probe, as a rule, are focused on the stationary arrangement of the probe between the devices [11-13]. In this case, a one-time section of the monitoring zone occurs between the subsequent monitoring of each network node of the corresponding section of the zone. This approach is optimal for solving a large class of problems.

Nevertheless, in recent years, decentralized networks have become more relevant, one of the most important advantages of which is the ability to dynamically change the configuration and adapt the solution to the monitoring problem to any changes in the conditions of the problem, provoked by factors of different nature. Thus, it is necessary to develop methods associated with finding solutions to similar problems [14,15].

It is in this ideology that models for the dynamic allocation of means of a spatially distributed continuous monitoring system are developed.

An original approach to the development of a simulation model for detecting moving objects of observation in a spatially distributed continuous monitoring system is proposed. The developed simulation model and the conducted experiments use the principles of dynamic detection of detection means in the area of a spatially distributed continuous monitoring system.

2. MATHEMATICAL MODEL OF THE DYNAMIC PLACEMENT

As the area of responsibility of the continuous monitoring system in this paper is considered the monitoring area which is bounded by a given square on the plane. Obstacles are placed in the monitoring area, represented in the form of parts of the plane bounded by closed curves. Neither monitoring objects nor monitoring tools can be placed or moved in these areas. Fig. 1 shows the layout of the monitoring objects in a given area of responsibility of the monitoring system.

In the general case, mountains, hills, insurmountable for ground and air purposes, water bodies, as well as elements of infrastructure in an urbanized area can be considered as obstacles. In the area of responsibility of the system (monitoring area), monitoring objects can freely move either along random or along specified trajectories, taking into account their technical capabilities.

Monitoring is carried out by means on the basis of Sensors, which at any given time can be located at a certain point in the monitoring area. Each monitoring tool has a limited field of view, which in planar projection onto the earth's surface is a circle of radius R. The radius of the field of view of each tool depends on the weather conditions in the monitoring area. Also, like the radius R, the speed of the Sensor in the area of responsibility of the entire system also depends on the weather conditions. In this work, the failure of monitoring tools is also taken into account.

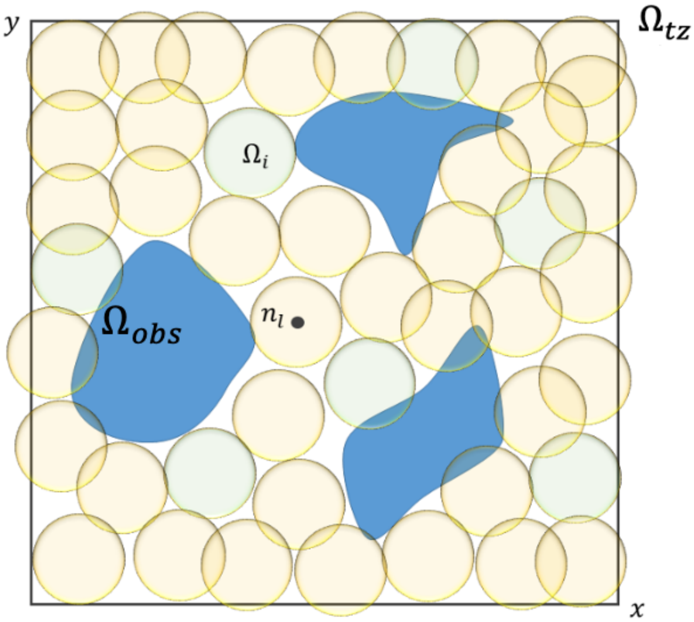

Fig. 1. General layout of monitoring tools in the area of responsibility of the system

To formalize the problem of placing detection equipment, the following designations are used (Fig. 1):

Ω_{tz} – a set of points of the system's area of responsibility,
S_{tz} – the total value of the area of the system's area of responsibility,
Ω_{obs} – a set of points of obstacle areas in the area of responsibility of the system,
Ω_i – a set of visibility zone points,
n_l – l-th vertex of the graph by dividing the area of responsibility of the system.

Assuming that the number of targets detected during the monitoring $t \in [t_1; t_2]$, inversely proportional to mean time $< t >_{[t_1;\, t_2]}$ detection of one target at a time $t \in [t_1; t_2]$, the following statement can be obtained:

$$< t >_{[t_1;\, t_2]} = \int_{t_1}^{t_2} dt' \cdot t' p_1(t'), \tag{1}$$

where $p_1(t)$ – probability density of detecting a monitored object at a point in time t.

Consider the case when the monitoring object is randomly located in the system's area of responsibility at the moment t_1 and does not move in the considered period of time $t \in [t_1; t_2]$. The randomness of the location of the monitoring object in this case, in the absence of a priori information, should be regarded as uniform. The assumption about the immobility of the monitoring object is valid provided that the speed of its movement is significantly less than the speed of movement of the sensors. ($v_{\text{OM}} \ll v_{\text{CO}}$). Under the condition of immobility of the monitoring object, normalization $\int_{t_1}^{t_2} dt' \cdot p_1(t') = 1$. To minimize the value $< t >_{[t_1;\, t_2]}$ дresidually minimize the standard deviation σ of the distribution $p_1(t)$. The value $p_1(t)$ can be represented as

$$p_1(t) = \frac{d}{dt}\left(\iint_{\Omega_{sw}(t)} dx'dy' \cdot p_1(x', y')\right), \tag{2}$$

where $\Omega_{sw}(t)$ – area of responsibility of the system, "swept" by means of detection at the moment in time $t \in [t_1; t_2]$, $p_1(x,y)$ – density of the probability distribution of the initial location of the monitoring object at the point (x,y). In the case of a uniform distribution of the initial location of the monitoring object $p_1(x,y) = 1/S_{tz}$, where S_{tz} – system area of responsibility. That is why expression (2) can be rewritten as:

$$p_1(t) = \frac{dS_{sw}(t)}{dt} \cdot \frac{1}{S_{sw}}. \tag{3}$$

Substituting expression (3) into expression (1), obtain:

$$< t >_{[t_1;\, t_2]} = \frac{1}{S_{tz}} \cdot \int_{t_1}^{t_2} dt' \cdot t' \frac{dS_{sw}(t\prime)}{dt\prime}. \tag{4}$$

Due to the fact that "sweeping" can occur only as long as $S_{sw} \leq S_{tz}$ (since at S_{sw}=S_{tz} the monitoring object will be guaranteed to be detected), the task of minimizing the average time of object detection has been reduced to the task of maximizing the "sweeping" speed (shown at Fig. 2).

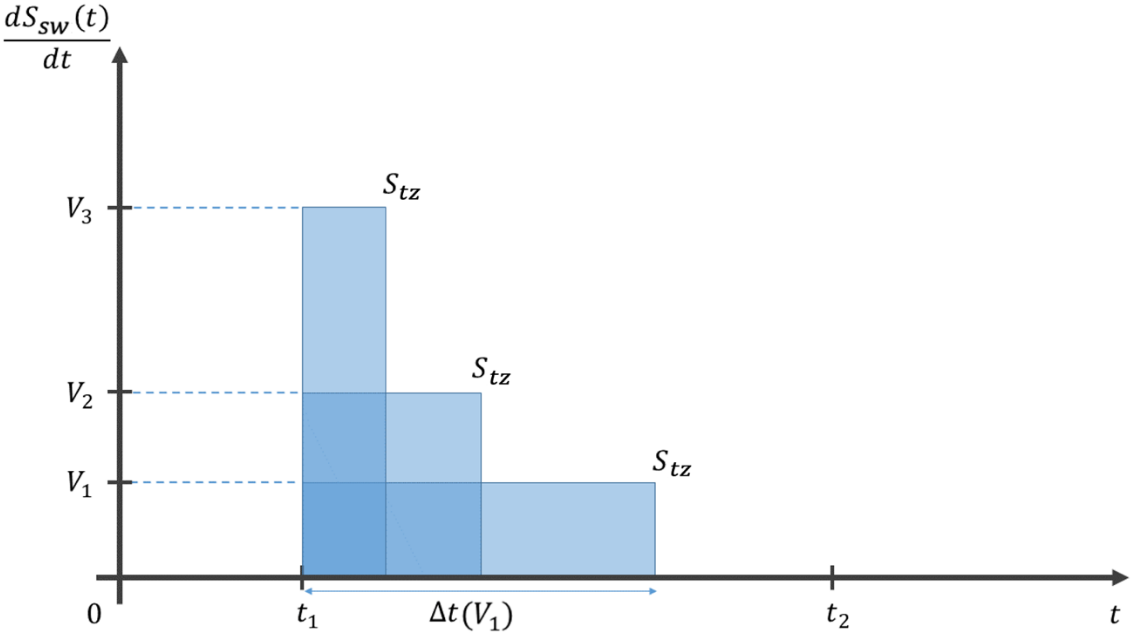

Fig. 2. Schematic representation of the effect of the "sweeping" speed on the length of the integration region in expression (4)

In the case when the monitoring object moves in the area of responsibility of the system for a period of time $t \in [t_1; t_2]$ (that is, when the condition $v_{\text{OM}} \ll v_{\text{CO}}$ is not observed), one pass of the detectors may not be enough to detect the monitored objects. In this case, it is necessary to launch an iterative patrol of the system's area of responsibility, in which at each iteration (or, in other words, in a cycle), the system's area of responsibility is swept along the routes (in both directions) that were used above when approaching a stationary target. Moreover, the less the period T_k (in time units) of traversing each point (graph node) of the target zone by monitoring tools, the faster the monitoring object will be detected. This statement clearly demonstrates the limiting case in which the period of the round trip of each point $T_k \rightarrow 0$. It should be noted that in view of the fact that the location of the monitoring object in the area of responsibility of the system is modeled by a random process with a uniform distribution over the area of the area of responsibility, none of the points is “selected”. Therefore, it is advisable to choose the same period of traversing each point, so $T_k = const$ for every k. Such a patrol mode can be carried out by a set of N detectors following each other along the constructed route at the same distance from each other. When the weather conditions change and / or the sensors fail, their location should be reconfigured at each subsequent moment in time, taking into account the new route and / or the new number of detection means of the monitoring system.

3. COMPUTER MODELING

Computer simulation is carried out in accordance with the following conditions:

1. The area of responsibility of the system is covered by nodes with a radius of the field of view under current weather conditions. Such a division is necessary to speed up the operation of the algorithm and is valid provided that during the time between two iterations in time, each monitoring tool has time to move to the next node along the route. At the nodes, a route is built along the terrain graph, which is a Hamiltonian cycle along which the detection means will move during the monitoring process.

2. At each iteration, the detector moves along the constructed route by exactly one node. A monitored object is considered detected (registered) if it falls within the scope of at least one detection tool.

For the computer experiment, the MATLAB software package was used.

It is proposed to carry out computer modeling of the deployment of mobile detection devices based on SENSORs in the area of responsibility of the system in the form of **four main stages**.

At the *first* stage, the input parameters of the task are initialized (the size of the monitoring area, the location of obstacles, the number of detectors, the size of the visibility area of one detector, the number of monitored objects, the speed of the monitored objects). The speed of movement of the detectors is determined by the size of their field of view, since in one iteration the sensor is shifted by a distance of the order of $2R$, where R – the radius of the visibility area of the detector, which is a circle centered at the sensor location. Thus, the average speed of each detection tool over the monitoring time is $< v_{sens} >_t \approx \; 2R \; pix/iteration$ ($2R$ pixel per iteration).

At the *second* stage, a graph of the movement of detectors in the area of responsibility of the system is built. For this, the area of responsibility of the system is covered by the visibility areas of the detection means. The location of the nodes is carried out by means of the gradient descent method, the function of which is the area of the covered area of responsibility of the system. The center of each of these scopes represents the top of the graph. Two vertices are connected by edges if the distance between them is $< 2R + 0.2 \cdot 2R$. An example of building a graph is shown in Fig. 3.

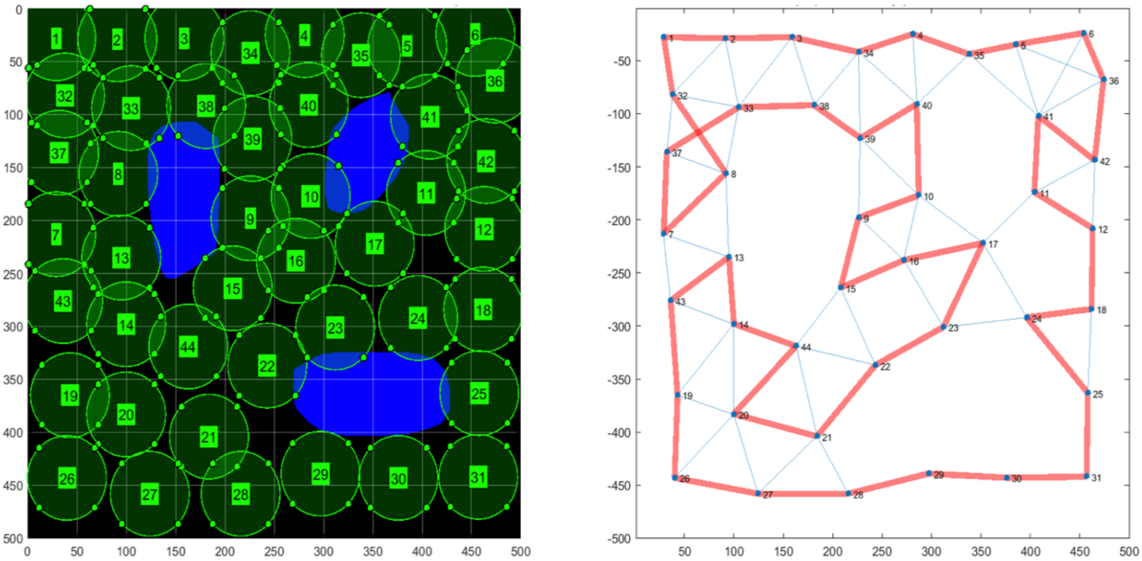

Fig. 3. Left: Filling the target area with sensor scopes. Right: building a graph of the movement of detectors based on this filling. The red line marks the Hamiltonian cycle

At the *third* stage, a Hamiltonian cycle of traversing all the vertices of the constructed graph is constructed. On the constructed cycle, detectors are placed with the same distance between two neighboring ones (if the distance is counted along the Hamiltonian cycle, see Fig. 4). Such an arrangement provides an equal traversal period for each vertex of the graph during the monitoring process.

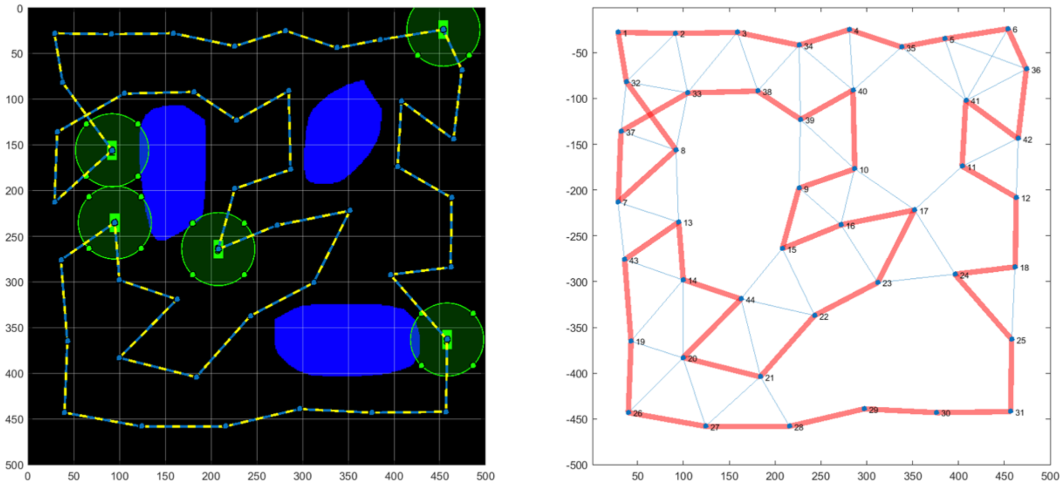

Fig. 4. Left: the location of the sensors on the Hamiltonian cycle.
Right: Hamiltonian cycle on the plotted graph

The *fourth* stage is directly devoted to the computer experiment. The number of detected (registered) monitoring objects is calculated for N iterations. At each iteration, the detectors are shifted along the Hamiltonian cycle by one vertex. The detected monitoring object is considered registered and cannot be re-registered in the future. The ratio of the number of registered objects of monitoring at the end of monitoring to their initial number determines the probability of object detection (registration) during the monitoring period. Monitored objects move in the system's area of responsibility in a random manner with equal probability at each iteration, the offset distance per iteration is initialized by the user and describes the speed of the monitored objects. A frame of an iteration of a computer experiment at a fixed time is shown in Fig. 5.

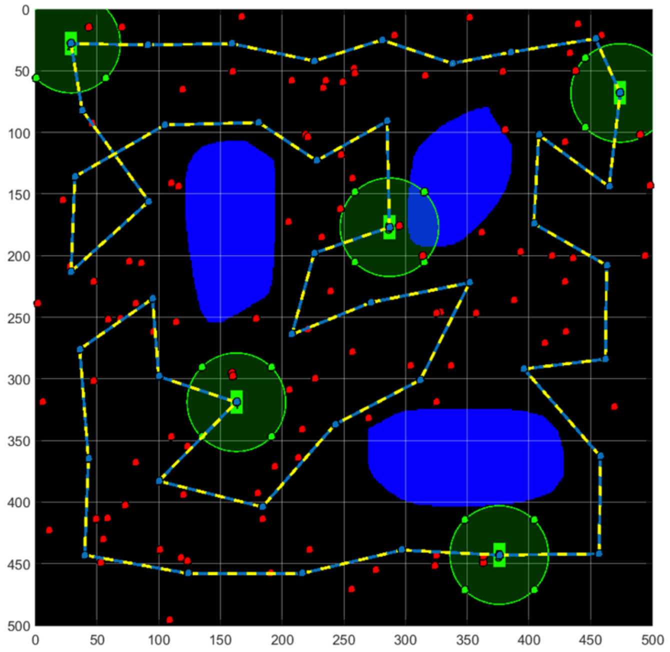

Fig. 5. A frame of an iteration of a computer experiment

4. RESULTS AND DICCUSSION

As a result of the experiment, was built the dependence $\frac{N_{reg}}{N_0}(v, N_{sens}) = P(v, N_{sens})$, which is the dependence of the share of registered monitoring objects on their speed and the number of detection tools. The share of registered objects of monitoring can be interpreted as the probability of registering one object of monitoring during the monitoring period. The experimentally obtained dependence $P(v, N_{sens})$ with an increase in the number of detectors is illustrated in Fig. 6 and 7.

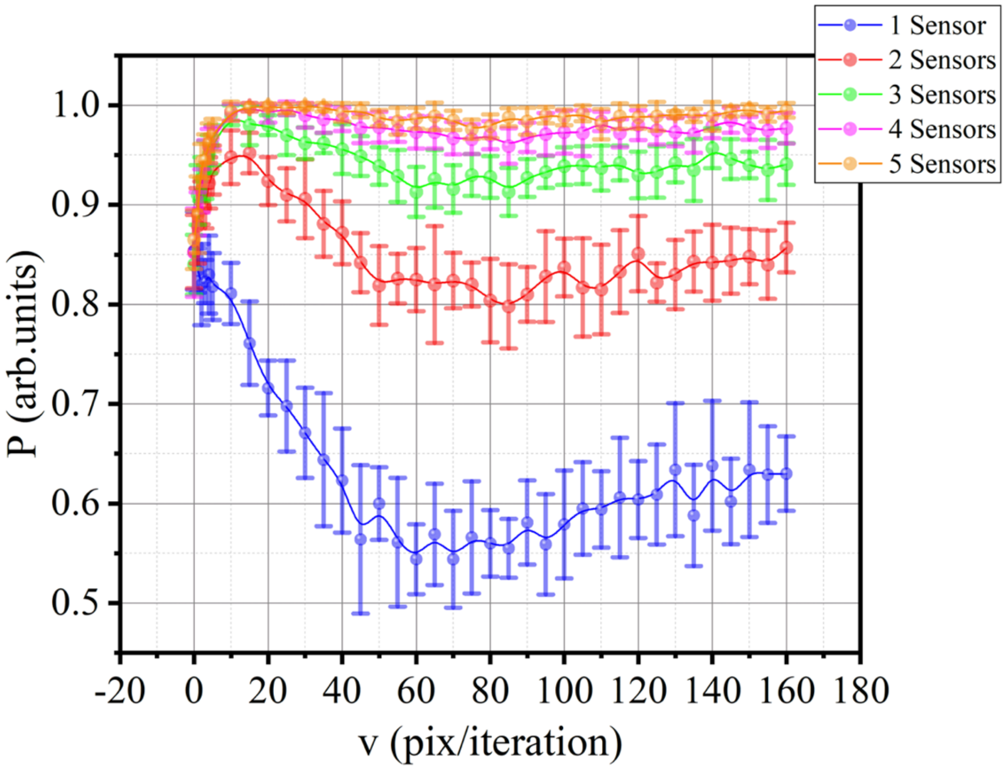

Fig. 6. Dependence of the share of registered targets on the speed of targets and the number of sensors

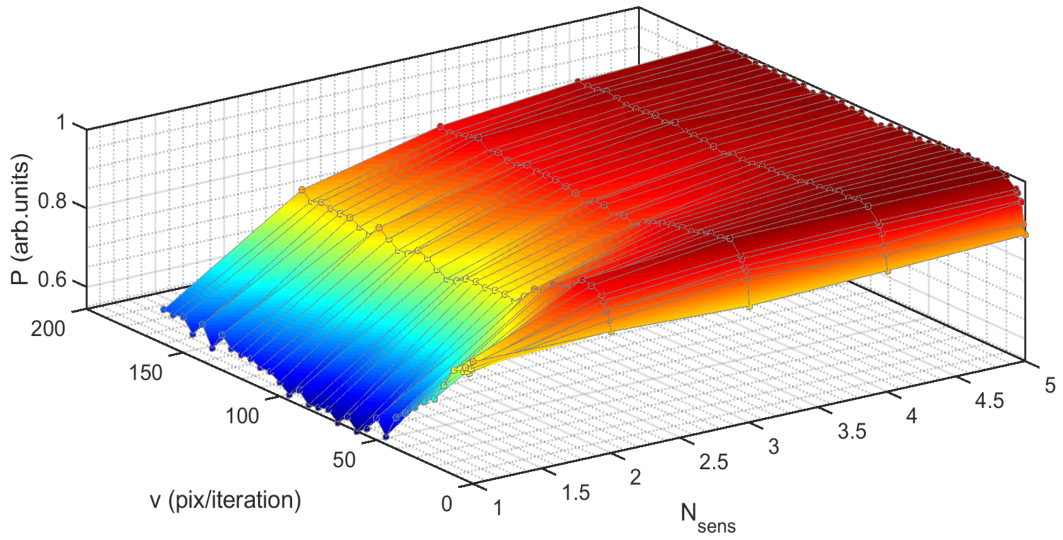

Fig. 7. Dependence of the share of registered objects of monitoring on their speed and the number of detection tools

The resulting dependence has characteristic features, among which the following should be noted:

1. There is an area of "stationary" probability, in which for any number of detectors the probability ceases to effectively depend on their speed, since addiction $P(v)$ this region has the character of small random deviations from the mean value, which we will call the stationary value of the probability P_{stat}. (see Fig. 3, left).

2. The dependence of the stationary probability on the number of detection means is approximated with high accuracy by the exponential growth function with saturation (see Figs. 6 and 8), i.e.

$$P_{stat}(N_{sens}) = 1 - \mathrm{e}^{-\alpha N_{nens}} \tag{5}$$

3. For $\mathrm{N_{sens}} = 1$ the dependance $P(v)$ is monotonically decreasing in the region until the stationary probability is reached. Therefore, at $\mathrm{N_{sens}} = 1$ the maximum probability of registering one monitoring object is achieved at zero target speed $v = 0$.

4. It is also of interest to study the dependence of the threshold point v_{th} transition to stationary dependence on the number of detection means. In Fig. 6 for $N_{sens} =$ 2,3,4 this point is shifted to the region of bigger speeds.

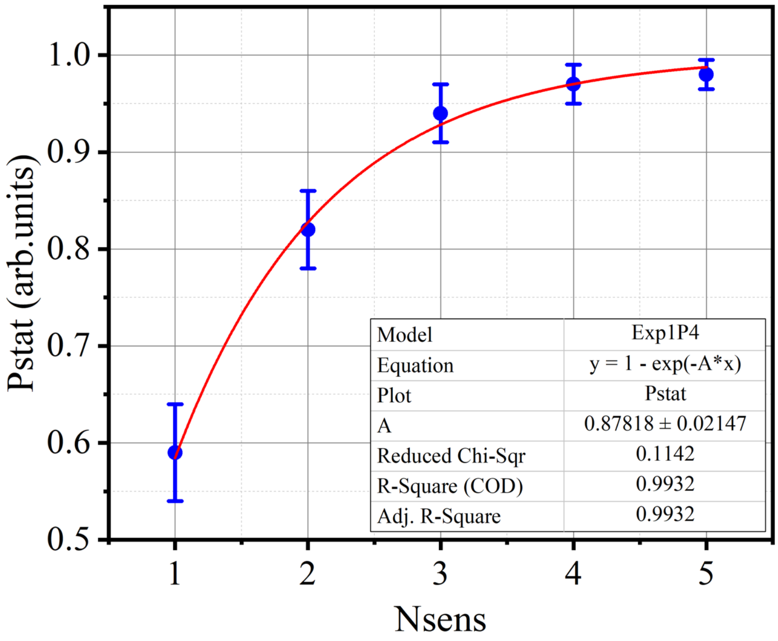

Fig. 8. Dependence of the stationary probability of registration of one monitoring object on the number of detection means

5. CONCLUSION

The proposed approach to optimizing the use of a continuous monitoring system makes it possible to efficiently register objects moving randomly in the area of responsibility. systems.

Within the framework of the budget work, a model that implements the ideology of the proposed approach. The model makes it possible to determine the optimal geometric arrangement, including the trajectory of movement of the means of a spatially distributed continuous monitoring system using the dynamic structure of dynamic targets. For a small number of detectors, the model allows you to find the optimal ratio of target speed to sensor speed. This, in turn, makes it possible to increase such an important indicator as to the probability of registration of one monitoring object.

The work investigates statistical dependencies, including:

- stationary probability of registration of one monitoring object from the number of detection means;
- registered objects of monitoring on their speed and the number of means of detection;
- registration of registered targets from speed and number of sensors.

The conclusions drawn from the analysis of these dependencies confirm the effectiveness of the proposed model.

In the region of stationary probability, an increase in the speed of sensors does not lead to a change in the probability of registering a target object in the singular. This allows us to conclude that it is possible to detect monitoring objects moving at a given speed, which makes it possible to determine such a threshold value for the detection rate when the efficiency of the system (from the point of the probability of object detection) exceeds the maximum values, which makes it possible to determine such a threshold value as optimal for solving detection tasks.

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