Method for Solution the Task of Analysis of Map Connectivity when Mapping the Spreading Area by Roboswarm with Communication

Vladimir E. Pavlovsky
Keldysh Institute of Applied Mathematics of RAS
Moscow, Russia
vlpavl@mail.ru

Vladimir V. Pavlovsky
Plekhanov Russian University of Economics
Moscow, Russia
vlpavl2000@mail.ru

***Abstract*— The mathematical model and algorithm solving a problem of the map connectivity analysis which is realized by the distributed information robotic system are described. Such task can be realized, for example, by a swarm of the flying robotic intelligent agents, for control of possibility of pass between obstacles of group of land robots which are given with the found information. The analysis of the map connectivity is made on the basis of special renumerating of areas of connectivity which is implemented by data exchange between robotic intelligent agents. The report is the reduced version of the publication in the "Artificial intelligence and decision making" journal (ISA RAS), No. 2. 2018.**

Keywords*— *The mobile robot; mapping; map; connectivity of the map

I. Introduction

Mapping problem, i.e. the problem of making a map, is one of key problems in supporting movement of mobile robots (MP) in complex or unknown environment. Such problems constitute a wide range of MP informational support problems, including scouting and exploring unknown areas, localization and navigation tasks, control or inspection of already-explored regions and other similar tasks. Due to importance of such tasks a lot of systems were developed supporting their solution. First of all there are systems showing landscape and obstacles on the map, such systems were developed for robots, robot groups ([1-3]) or to assist humans working in natural environment [4]. Many recent researches were focusing on developing systems for simultaneous mapping and navigation of robots – SLAM class systems (Simultaneous Localization And Mapping) [6-10]. But it is important to note that most of these systems are limited to determination of external contours (overall dimensions) of obstacles, while in many applications it is also important to explore internal "topology" of obstacles, in particular if their dimensions are significant.

Our work deals with a swarm of robots, with each robot having the same and sufficiently simple behavior model. Of interest is the possibility of synthesizing complex behavior of the swarm as a whole and making the swarm to solve meaningful tasks basing of relatively simple rules for separate robots-"individuals". The aim of our work is making the swarm to analyze environment; in particular - area map analysis. Such tasks are well suited for distributed systems.

In this work we have chosen one of the most fundamental topological properties of the map - connectivity. It is supposed that there are some objects located in the area - obstacles or landmarks and robots are equipped with proper sensors to detect them. Swarm task is to determine amount of connected components that these objects divide the area into.

On one hand, such problem of connectivity analysis for an area divided by obstacles arises from the question of passage existence - and further could be developed towards searching path through a labyrinth. For example, a swarm of flying robots can study landscape from above and suggest route for ground group.

On the other hand, this task could be seen as a step to distributed analysis and recognition of images. For example, well-known drawings (geoglyphs) in Nazca Desert are of huge size and could not be seen from ground as a whole - understanding of these images only came after aerial photography. But aerial photography could not be performed under limited visibility conditions - fog, smoke or underwater. In such case analysis of such objects becomes a suitable task for a swarm of robots, each one only observing separate element of the image, with swarm determining properties of the whole image through communication. Therefore the last example in this report shows the model applied to a photograph of one of the images in Nazca Desert.

II. Mathematical model and algorithm for solution the task of analysis of map connectivity

Mathematical model used in the work is the following. The problem solution is divided into two sequential stages:

1. Spreading of the swarm in the area being explored. The swarm moves into the target area and spreads, forming a big cloud.
2. Analysis of geometrical properties of the map. On this stage the swarm is considered stationary. It is supposed that after completing this stage swarm returns to its

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origin point and "turns in" the completed task, i.e. transfers the solution to whoever requested it.

On the spreading stage robots should move into area being explored and form a dispersed cloud. To configure swarm for this desired behavior we used the concept of "pseudoforces", developed in [5], that "push" robots in desired directions. These, however, are not physical interactions, but rather behavior rules - robot "desire" to move in specified direction. And therefore, contrary to physical forces, pseudoforces define not accelerations, but speeds of robots. This approach both simplifies control and prevents undesired modes such as oscillations. At the same time, proper choice of this function could be used to program robots to synthesize desired behavior of the swarm as a whole.

In order to form dispersed cloud we define the pseudoforce acting on the robot number k by equation:

$$\overline{F} = -\sum_j f\left(\left|\overline{r}_j - \overline{r}_k\right|\right)\frac{\overline{r}_j - \overline{r}_k}{\left|\overline{r}_j - \overline{r}_k\right|} + K_3\frac{\overline{r}_T - \overline{r}_k}{\left|\overline{r}_T - \overline{r}_k\right|} + K_4\frac{\overline{r}_T - \overline{r}_A}{\left|\overline{r}_T - \overline{r}_A\right|}$$

Let's explain this formula in detail. First component is the sum over all other robots and defines repulsion of robots from each other which is the key element leading to desired swarm dispersion. Function *f(r)* defines strength of this repulsion and is computed as maximum of two functions

$$f(d) = \max\left(K_1 f_1(d), K_2 f_2(d)\right)$$

$$f_1(d) = \begin{cases} 1 & d \le d_1 - \Delta \\ \left(d_1 - d\right)/\Delta & d_1 - \Delta < d \le d_1 \\ 0 & d > d_1 \end{cases}$$

$$f_2(d) = \begin{cases} \left(1 - \dfrac{d}{d_2}\right)^2 & d \le d_2 \\ 0 & d > d_2 \end{cases}$$

where $d_1 > d_2$, $K_1 < K_2$. As could be seen from the formulas, first value $K_1 f_1$ is constant to fixed radius d_1 and then decreases to zero. This is the primary pseudoforce defining dispersion of the swarm. Combined with weaker attraction towards the center that is defined by the last two addends of the main formula above, this repulsion leads to neighbor robots spreading approximately at distance d_1 from each other.

Second value $K_2 f_2$ only acts in a small radius d_2, but has fast quadratic growth. This pseudoforce, introduced in [5], prevents robot collision if for some reason (such as repulsion from other robots of the swarm) two robots move too close to each other.

As could be seen from these formulas, the repulsion force defined by function *f(r)* equals zero beyond certain radius, so the sum in the first component of the main formula essentially only includes robots in certain neighborhood, and therefore could be determined by each robot locally.

Second and third components in the main formula define swarm "attraction" to the target - area to be explored, its center defined by coordinates r_T (*Target*). Second component defines attraction to the target directly for the given robot. However, having this component alone has led to the following problem: if the attraction constant K_3 was too big, the cloud of robots became too non-uniform - condensed towards the center, because robots on the edges were attracted to the center and their repulsion further pushed central robots inside. And with smaller values for attraction constant K_3 robots were too slow in their movement towards the target.

Therefore the last component was added, describing attraction of the swarm as a whole to the target. In this formula r_A is the center of "mass" of the swarm, computed as the average of coordinates of all robots, $\overline{r}_A = \frac{1}{n}\sum_j \overline{r}_j$.

This components help to "push" the swarm towards the area it has to explore without causing any deformations of the cloud. Coefficients are chosen in such a way that K_3 is relatively small and $K_4 > K_3$. Second addend in the main formula is still required, even though K_3 is small, because otherwise repulsion of robots could lead to fragmentation of the cloud. Weak attraction of all robots towards the center serves to ensure both integrity of the cloud and roughly round shape while not interfering with robots spreading to set distance.

Completion of the first stage could be determined either by the condition of robots ceasing to move significantly (simulation shows that the swarm quickly stabilizes after moving to the desired area and spreading) or simply by timer, allowing certain time for this stage, after which robots stop their movement and advance to the second stage.

On the second stage, map analysis stage, we suppose robots to have spread over the area and not moving anymore. After that each robot determines if it sees the objects being mapped inside certain radius around. As said above, we suppose robots to be equipped with some sensors to do this, which we abstract in the model. Instead for each robot a fixed neighborhood of radius r_1 is defined and we suppose robot to know if this neighborhood intersects with any of the objects in the area.

Using this information, connectivity analysis is performed by the following algorithm which is based on the wave algorithm (similar to routing algorithm, using wave spreading of data – robot numbers):

1. Each robot stores a numerical variable - its number. At start each robot is assigned a different number from 1 to *N*, where *N* is the amount of robots in the swarm.
2. After detection stage those robots that see any obstacles replace their number with -1 and do not participate in further analysis.
3. Each robot, using it communication equipment, connects to all other robots in fixed neighborhood of given radius r_2. Let number of this robot be x and number of its neighbor robot be y. If $x > 0$ and $y > 0$ and $y < x$, then robot replaces its old number x with its neighbor number y. In other words, for each such pair of neighbor robots that neither of them sees obstacles, robot with higher number replaces its number with the smaller number of its neighbor.

4. Operation 3 is repeated until robot numbers stop changing.

During operations 3 and 4 each connected component of the area is gradually filled with smallest of the numbers assigned to robots falling into this area – as a result all robots in this component will get this number, while in other components numbers assigned to all robots will also be the equal, but different. Therefore, the amount of connected components will be equal to amount of different numbers remaining in the swarm (besides number –1).

In this algorithm r_1 и r_2 are parameters – they are, respectively, radius of visibility (detection) area and robot neighborhood area. Neighborhood area is the area where the "working zone is localized" of the algorithm described above.

In the simulation to simplify computations areas of visibility and neighborhood were both defined as disks with same center, visibility area laying inside neighborhood area. Best simulation results were obtained with radius ratio of $r_2 = 2r_1$.

III. Examples of the simulation program work

Now we present several images – examples of the simulation program runs. First consider a simple ring obstacle.

Fig. 1 and fig. 2 show initial configuration, spreading of robots, spreading completion and analysis completion – two connected components were found.

On the analysis completion phase (fig.2 right) special color state markers are drawn upon robots – they show if the given robot is seeing obstacle or what connected component it has determined.

Further on fig. 3 another working moment of the simulation is shown – analysis of a drawing (geoglyph) from Nazca Desert.

On the last picture a lone robot in the bottom part is noticeable (marked by a white arrow) that has found an "extra" component: while this component has an exit, it is too small and robots are not many enough, their visibility radiuses are relatively big, and therefore swarm resolution was insufficient to recognize this exit.

We note that for the experiments we have modified our simulation software system described in [5]. All images of the simulation episodes above in this report were obtained with this program. Series of experiments were performed simulating the developed algorithm. Algorithm was shown to be stable and sufficiently efficient.

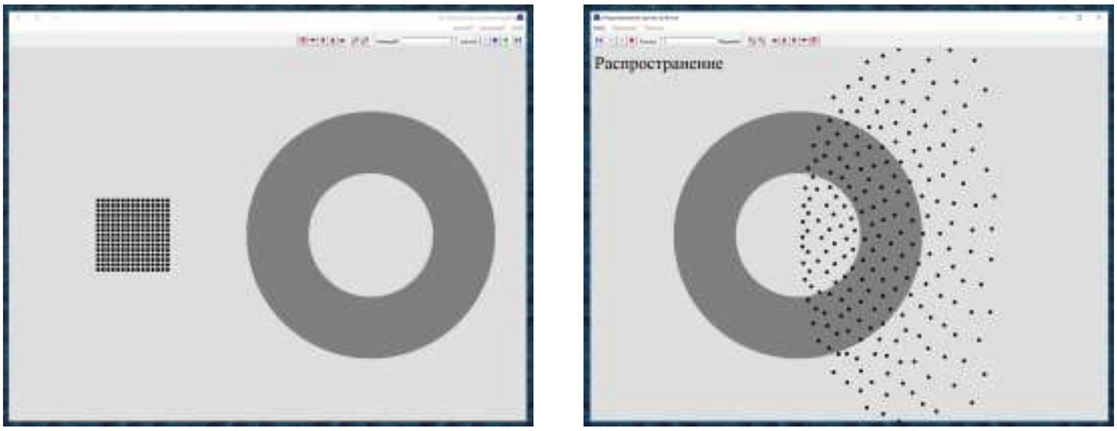

Fig. 1. Initial configuration, spreading of robots

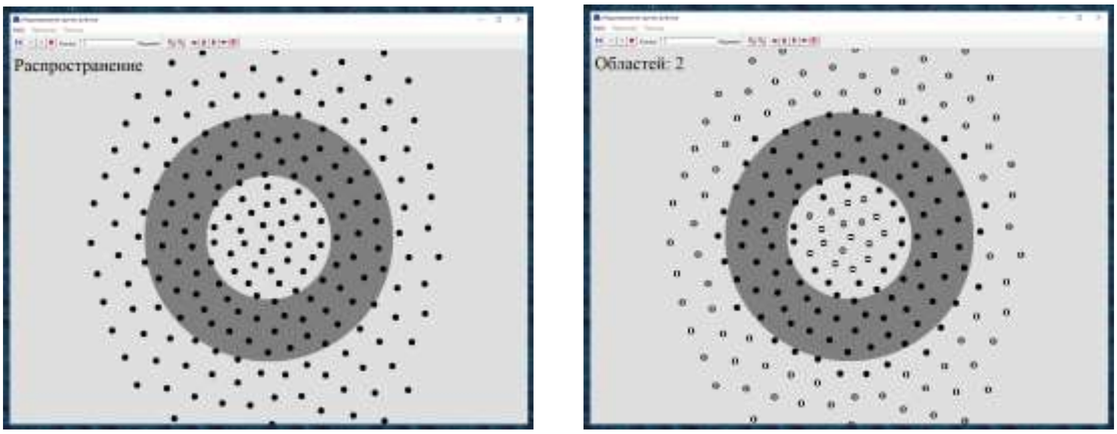

Fig. 2. Spreading completion and analysis completion

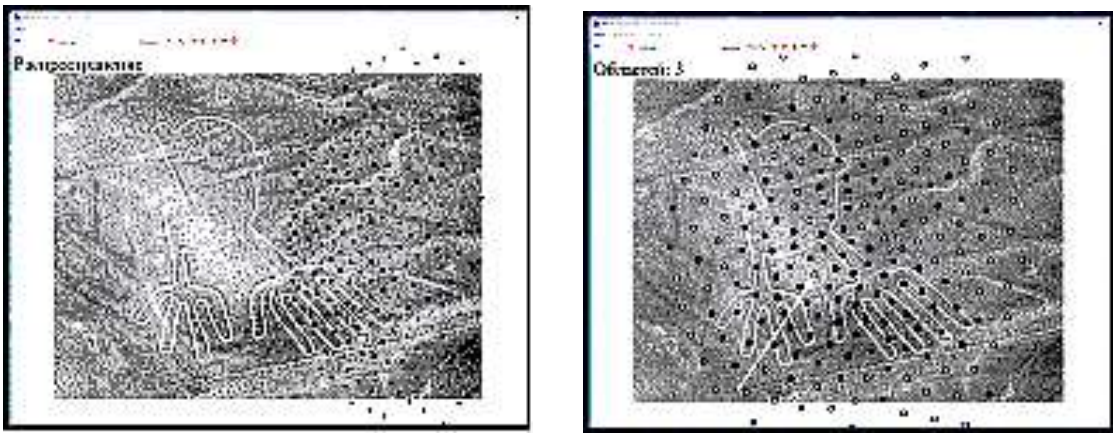

Fig. 3. Geoglyph from Nazca Desert

IV. Conclusion

Thus as a whole we can note that the method is efficient, but recognition of images with small details requires swarms of large amount of robots with small precise visibility areas. To further this research we intend to consider evaluation of such amount of information robots required for a given task.

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