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OPTIMIZATION, SYSTEM ANALYSIS, AND OPERATIONS RESEARCH

"Pitfalls" of Bio-Inspired Models on the Example of Ant Trails

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Abstract—This paper explores the problem of influencing the environment by a group of autonomous robots through the creation and use of road infrastructure. The model object is ant roads (trails). We identify the main aspects of the behavior of different ant species in the process of collective foraging, and actions that together lead to the appearance of a phenomenon that the observer perceives as an ant road. We develop and describe an animat behavior model in the process of arranging a route. We define a list of mechanisms, a set of sensory capabilities, and effectors that are necessary for the robot to implement options for arranging the route. The results of simulation modeling for solving the foraging problem with route clearing are consistent with theoretical models. The simulation results confirm our assumption that the route arrangement can be carried out by individual efforts of animats (robots) and without the need to organize joint actions.

Keywords: social behavior models, collective robotics, autonomous mobile robots, bio-inspired models, foraging task

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1. INTRODUCTION

Usually, the task of moving autonomous agents (robots) is solved by methods of constructing an optimal or suboptimal route. If the robot has an environmental map and the starting and ending points of the route are determined, then various optimization methods are used to solve the problem [1]. If there is no map, the robot either pre-builds this map (SLAM methods, Simultaneous Localization and Mapping), or the map is constructed with the target point search [2]. Some of the methods used take into account changes in the environment, but practically nowhere is the problem that a robot can change this environment itself considered. For example, if there is an obstacle that prevents the robot from moving in the right direction, it can bypass the obstacle or remove it if it is movable and the robot has manipulators to move it. Here the problem arises of finding a balance between the costs of bypassing the obstacle and clearing the road.

There are two aspects to this work. On the one hand, the behavior of an agent moving along the route will be considered from the point of view of the bio-inspired methods application. On the other hand, this problem is used to raise the question of the technical inexpediency of modeling the external, phenomenological side of animal behavior instead of identifying and implementing the basic mechanisms of their behavior.

The use of social behavior models (SBM) is one of the approaches to solving complex tasks of group robots control in difficult non-deterministic environments. SBM consider the socio-inspired organization of robot interaction as one of the adaptive mechanisms that allows solving group tasks in complex dynamic environments where the use of centralized control methods is difficult or impossible [3, 4]. Here the term "society" is considered as an exclusively biological concept.

Ants are a prime example of social animals. They form so-called *eusocial communities* — the most complex form of social organization. This community is characterized by such signs as the presence of a territory assigned to the group, a permanent composition of the group, cohesion (the desire of group members to stick together), individuals specialization, etc. [5, p. 109].

The use of SBM to solve group robotics tasks is as follows: formalization of various behavioral patterns of social animals; development of mechanisms and algorithms that implement these models; creation of software and technical solutions based on them, allowing to perform applied tasks of group robots control. Previous research in the field of SBM has focused on the interaction of agents with the environment and with each other. Now the issue of agents influencing the environment is becoming relevant.

SBM belong to bio-inspired approaches, therefore, the issues of methodology for creating bio-inspired models are important.

2. METHODOLOGICAL ASPECTS

There are two extremes in the field of bio-inspired models related to the modeling of social behavior of animals. The first is to create artificial models "inspired by nature." These are Ant Colony Optimization algorithms [6], Grey Wolf Optimizer [7], Butterfly Optimization Algorithm [8] and similar stochastic algorithms [9], optimizing the search in the solution space. For example, the Ant Colony Optimization algorithm is based on the concept of a pheromone trace [6]. Some ant's species leave an odorous trail: a pheromone that evaporates over time. Foraging ants move in the direction of increasing the intensity of this odor when searching for resources. The pheromone analogue serves as the basis for gradient search in a solution space. Another example is the Gray Wolf Optimizer algorithm (GWO). The GWO mimics the hierarchy of individuals and hunting mechanism of grey wolves in nature [7]. This algorithm contains many biological terms, but in fact "individuals" are solutions in a space that is described by some non–monotonic function. At each step, the algorithm evaluates three best solutions, then the "individuals" are shifted in space according to certain rules, the solutions are evaluated again under the assumption that the best solution is located in the geometric center of the "dominant" individuals. Thus, this algorithm is a completely artificial mechanism, for which only the general principle of dividing individuals by weight in decision-making is taken from nature. Such methods solve optimization problems well, but have little to do with the actual behavior of living organisms.

The other extreme is an attempt to simulate natural mechanisms in the form in which they are observed in nature (a phenomenological approach). The authors take certain natural phenomena, more precisely, a description of human observations of these phenomena, and model their external effects. This approach leads to the emergence of numerous realizations of these phenomena. For example, in [10, 11], the authors describe an implementation of ant foraging, which is a complex behavior and involves the search and transportation of food. Other authors even propose "generalized approaches" to such modeling [12]. But all these solutions are particular ways of solving specific problems.

One of the most striking examples is aggression or agonistic behavior. Quite a long time ago, biologists proposed to consider aggression as an external manifestation of certain social behavior types, such as parental, nutritional, etc. [13]. But so far, aggression is explicitly or implicitly declared a basic mechanism or a separate behavior type (see [14, 15]). However, this phenomenon can be realized with the help of other basic elements [16].

In contrast to the above approaches, the SBM paradigm assumes that any complex social behavior or phenomenon consists of a small number of basic mechanisms. This corresponds to the approach of M.L. Tsetlin school in the field of collective behavior [17]. To model behavior, it is necessary to understand what basic elements it consists of and how the observed effects arise, not to introduce unnecessary entities, but to use a combination of basic mechanisms to implement any behavior. This has both a technical and a pragmatic rationale.

As an example, let's give the phenomenon of leadership. Leadership is just some observable phenomenon. The individual does not have a special "leader" block, and insects do not have specific tasks related to dominance. It's just that the behavior of an individual depends on the presence or absence of other individuals nearby. If there is someone stronger (larger, well-fed, etc.) nearby, then the individual begins to behave like a subordinate — it follows the leader. Following a leader is understood in a broad sense: both movement and imitation of the leader's actions in the end. This is one of the basic models of social behavior [5, 18]. If there is no one more successful or stronger nearby, then the individual itself becomes someone whom others perceive as a leader. The individual itself does not perform any "leadership functions", but continues to do its own actions — construction, foraging, etc. And we observe the effect of self-organization: individuals next to the "leader" begin to perform similar work.

Another good example is the phenomenon of ant roads. This is a well-established term often used in literature [19–21]. In this paper, we will try to show that the term "ant trails" appeared as a result of human interpretation of the observed actions of individual ants and their groups, which are usually performed during foraging.

Trail construction is considered one of the most interesting examples of ants working together, which has an impact on the habitat. There are many descriptions of how roads arise, how they are maintained in working order for a long time, etc. Therefore, the desire to model this mechanism is justified, in particular, in order to efficiently use resources or minimize energy consumption during movement. However, an attempt at formalization leads to a rethinking of the road phenomenon in determining the mechanisms underlying it.

The first question is: what are we really observing? The answer to this question determines which models and mechanisms need to be implemented. Strictly speaking, a trail is not only an element of infrastructure. A trail or road is a concept included in the agent's knowledge base about his environment, part of the so-called world model. From the point of view of semiotics as the science of sign systems, which determines the applied aspect of the knowledge representation form, this concept should include the image (perception of the sign), ways of using it (meaning of the sign) and influence goal setting (personal meaning of the sign) [22]. Formally, the sign S describes the entities or concepts of the agent's world. It can be represented as follows: $S =< n, p, a, m >$, where n is the sign name, p is the perception (description or set of characteristics), m is the sign meaning (procedures related to the concept), a is the personal meaning (the component responsible for goal setting).

On the other hand, there is the concept of *a route.* This is a fundamentally different entity. This is an observable external; it does not have to be part of the agent's world model. As will be seen later, the "road" activity of social insects can be reduced to the arrangement of routes. We will understand the route arrangement as a set of actions performed on the area through which the route runs, and aimed at changing its physical characteristics in order to reduce the energy costs of passing the route.

3. TRAILS AND ROUTES

The road aspect is very interesting for group robotics (GR). GR solves practical tasks such as monitoring, reconnaissance, patrolling, etc.; therefore, moving along certain routes plays an essential role. Important mechanisms are not only cooperation and coordination of actions, but also the creation of road infrastructure by robots themselves during self-organization. Researchers do not pay enough attention to the latter issue, although the benefits of clearing a route to increase movement speed, for example, are obvious.

Biologists consider roads to be one of the main structure elements of the protected area of many ant species [20], and the roads construction is a vivid example of collective behavior [23]. But an attempt to find a definition of the ant road did not yield results. Biologists often use terms without giving any definitions at all. For example, one of the prominent Russian researchers A.A. Zakharov gives a classification of ant roads, but does not define the road [19]. Biologists from other countries use similar terms: trails, trail construction [24], infrastructure construction [23]. But they also do not give definitions, at best they give a brief description, for example: "physical trails, i.e. pathways that are cleared of obstacles" [24]. And it gives the impression of "well-established terminology" from the category of "everyone knows what ant roads (trails) are."

Let's try to approach this issue from a constructive point of view. We will understand by a road **a strip of land equipped or adapted and used for movement, or the surface of an artificial structure**, i.e. something that is the result of purposeful activity. This is similar to the definition that can be found in official documents.

Such definitions are not constructive for SBM. This is an exclusively external phenomenological description. To implement behavioral models, it is necessary that the road become the essence of the agent's world model. It should be a kind of sign that has at least two components: a number of signs recognized by the agent (perception) and many related behavioral procedures (meaning). But besides the term "road" there is the concept of a path or route. A route is a way from one point of interest to another. The route is recorded or evaluated by an external observer, i.e. he does not have to be represented in the agent's world model.

In this work, it is assumed that in the ant world there is no road as a specially created structure, but there is a route, for example, from the nest to the foraging area. There are many confirmations that the concept of "ant road" is a human interpretation of the movement of ants along a certain route. For example, in [21, p. 38] it is said about determining "the direction of forage roads or *forager flows* in cases where there are no permanent roads." Or in [20] when describing roads deep into the soil: "In the rest of the territory, ants used *ordinary roads which represent a stream of foragers* while actively using trunks and branches of fallen trees to move."

Let's further consider the two main *road* phenomena described in insect biology, replacing the term road (trail) with the term **route**.

3.1. Route Formation

Let's describe the process of forming the ant's route based on data from [21, p. 10]. First, the scout ants explore the area in search of food resources (for example, aphid habitats). If scouts discover new food source, they return to the nest, mobilizes its nestmates and take them to this place. If it is a renewable resource, foragers begin to visit this place regularly. The route usually does not run in a straight line, but where it is more convenient to walk: partially along fallen branches and tree trunks. But if the route passes over the ground then there are irregularities, small debris, vegetation that interfere with walking. Then the ants begin to arrange the route to make it more "convenient," reducing energy costs. One removes debris, the other pushes aside soil particles, the third destroys small vegetation. The surface is leveled, and the route sometimes becomes more direct and shorter. As a result of the individual, over time, the same "cleared trail" is formed [24], which the observer sees. People perceive this usually narrow cleared strip along which ants move as a road or trail (Fig. 1). In places, it passes through fallen branches or tree trunks (Fig. 1a) [20–21, 23], then it can only be detected by the ants flow. But on the ground, this "trail" is clearly visible even in the absence of ants on it (Fig. 1b), and the observer may have

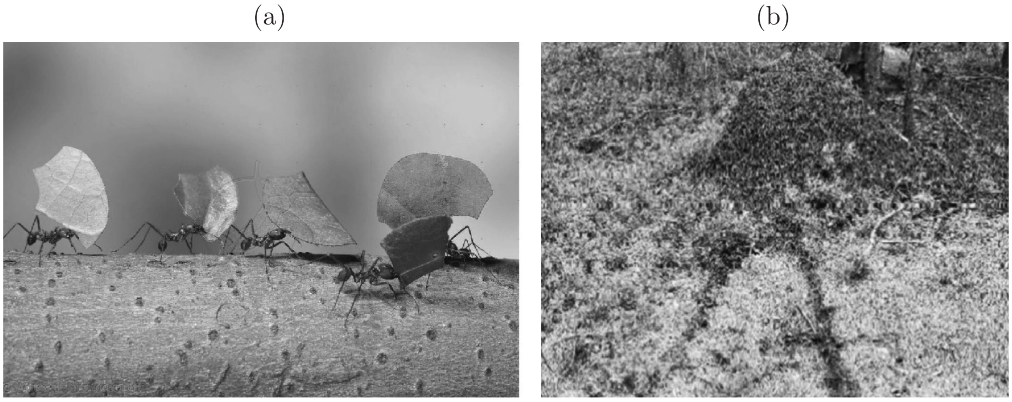

Fig. 1. Examples of "ant roads": (a) a stream of leaf-cutting ants passing along the trunk of a tree; (b) an anthill of a red forest ant with two "roads."

the impression that he sees a certain construction that appeared as a result of coordinated actions (construction).

It is convenient to call this "construction" a road by analogy with human roads. But for a person, a road is a construction with a certain set of signs that determine human behavior in relation to it. Ants do not have such unambiguous recognition. The experience indirectly confirming this is described by A.A. Zakharov [21, p. 11]. On one of the roads, the researchers seized all foragers and observer ants from the side of the nest adjacent to the road. Thus, there are no ants left in the nest that know this road. The ant family regained possession of the lost part of the territory a few days later, but the original road network and many aphid colonies in the experimental sector were lost. Consequently, other ants who do not know the area could not recognize the roads that exist on it and reuse them.

3.2. Clearing the Route

On the one hand, the ant's activity in "road maintenance" is energetically beneficial. For example, loaded leafcutter ants travel 4–10 times faster on cleared trails than on uncleaned ones [25], and on average a colony of such ants spends only a few days per season clearing trails [26]. On the other hand, there are studies [23] with the same leafcutter ants, confirming the hypothesis that there are no feedback mechanisms between individuals, nor recruitment mechanisms specifically for clearing the trail. The mathematical model [23] shows that the results of trail clearing experiments can be explained by a fixed probability that the forager will eliminate the interfering obstacle, and this does not require the mobilization of other ants.

So, using the concept of a route, we can explain all the observed phenomena of the appearance, use and support of the "road ants infrastructure," more precisely, the rational use of the territory.

This statement may seem unnecessarily categorical. We will not delve into terminology issues, we will talk about tunnels [27], roads deep into the soil [20], etc. Of course, environmental change affects the nature of the agent's behavior: he will *preferably* move along a convenient, well-trodden area. In this sense, the tunnel is the ultimate case of such a "preference", because in the tunnel the ant does not have the opportunity to choose another path. Let us repeat that if we consider the road not as the essence of the world model of an external observer, but as the essence (sign) of the agent's world model, then behavioral procedures (the sign meaning), its image (perception), and meaning (explicit meaning from the point of view of the objective function) should be associated with such an entity-sign. But exactly all this is not observed in the agent's behavior.

4. THE ROUTE ARRANGEMENT

Based on the above, we will assume that ants do not have a separate type of activity for the construction and maintenance of road infrastructure. Individual foraging ants, moving along a familiar route, perform some actions. The result of these actions is perceived by an outside observer as a road. These actions are auxiliary. Therefore, the solution of the task of arranging the route should, if possible, be performed using methods and mechanisms that have previously been implemented and have already been used for other tasks, and not introduce entities beyond what is necessary.

The agent must move from one point to another to solve various tasks: patrolling, foraging, etc. Here, the task of movement is solved not at the level of route planning and building an optimal trajectory, but at the behavioral level (like ants). Let's take foraging as an example. Foragers regularly go to the food source and move it to the "base," and the route connects the base and the source location. The agent does not have an environmental map (like the ant [28]): he remembers the route by visual landmarks and compass [29, 30]. During the movement, the agent remembers landmarks and approximate compass direction, so his route is a set of relatively straight segments from one landmark to another (Fig. 2).

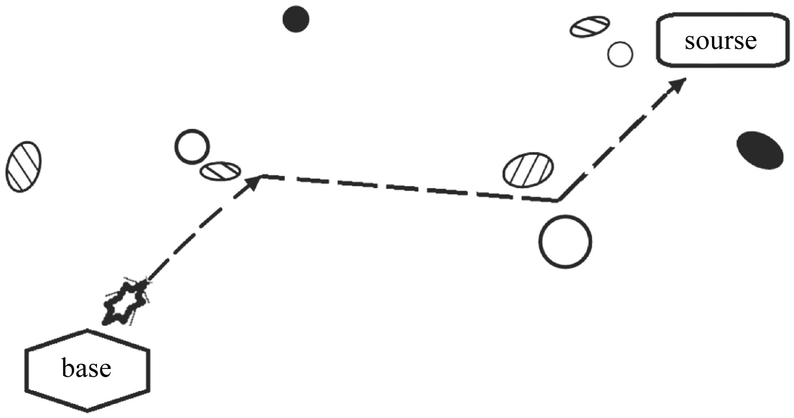

Fig. 2. Example of a route from a "base" to a source.

Movement characteristics. The direction of the agent's movement is determined by the local goal and context at every time. A local goal for ants can be a visible landmark, a pheromone trail, polarized light data. The current context is the state of surface, obstacles, etc. The context determines the characteristics of movement, obstacle avoidance, local preferences, etc. In this sense, movement is the "resultant" of tendencies to go in the right direction, as well as to go in such a way that it is "more convenient." This is precisely the effect of the "trodden" path on the agent's movement. The more intense the flow, the more the path is "trampled," the more preferable it will be to move along it. But such a "well–equipped" route is not a road, it's just "more convenient" to go that way.

The efficiency of movement is determined by energy consumption, which depends on the time of movement along the route. The time depends on the total length and curves of the route: the agent moves in a straight line faster than when turning, in particular, when bypassing an obstacle. Thus, removing obstacles and straightening the route will increase energy efficiency. In addition, the number of landmarks that the agent can recognize should be sufficient for steady movement along the route. This increases the probability of successful passage from the base to the source and back.

The route arrangement for ants in general may include different actions:

1. Trampling (compaction of the soil without additional effort of ants).
2. Clearing the route (cleaning up debris and vegetation).
3. The use of improvised material to increase the convenience of passing along the route, for example, laying plant debris on a swampy route section.
4. Surface leveling, including digging into the soil.

The procedure for clearing the route. When an agent goes along a known route, he knows in which direction he needs to move. If there is an obstacle in front of him that prevents him from walking straight, he can bypass it or move it to the side. To do this, it must recognize obstacles and distinguish between movable and non-movable ones. He can perceive these same obstacles as landmarks.

The clearing procedure determines where and how the obstacles are removed. The main question is not in which direction or how far the interfering objects are moving. Difficulties arise when obstacles shift into piles or shafts, forming new landmarks. In fact, the creation of a new landmark means the agent's explicit impact on the environment.

Note that using displaced obstacles as new landmarks is not the same as reacting to a pheromone trail. On the one hand, if an agent detects such a landmark, it cannot identify it as a landmark along the path. On the other hand, the pheromone in ants is a label that is perceived by ants as a sign that another ant's route is passing here. The odorous trail left by the scout can be used by foragers for self-mobilization: they begin to move along this trail in the direction from the nest (they know its location) [31]. In the case of moving an obstacle, only the agent who walks along the route known to him can remember this obstacle as a landmark.

Participants in the clearing. Any forager can become a participant in the clearing, since there are no special clearing ants [32]. The probability that an ant will start clearing depends on its condition. Foragers carrying cargo are never engaged in clearing (for leafcutter ants, see [23]). There is also an estimate of the probability that an ant, when faced with an obstacle, will eliminate it.

So, clearing a route leads to its opening, a reduction in its length and to the creation of additional landmarks along the route.

5. THE AGENT'S BEHAVIOR MODEL FOR ROUTE ARRANGEMENT

Biologists' research confirms that the route arrangement in ants is energetically efficient [25, 26]. Consequently, the assessment of the agent's actions during foraging can also be based on changes in energy costs. Here is a model describing this process and allowing evaluation of the effectiveness of the agent. This is a simplified qualitative model; it does not aim to describe all the details of the route clearing process.

Suppose there is an agent solving the problem of transporting some resource ("food") from the foraging area to the base. The amount of "food" determines the positive contribution to its energy balance. The agent expends energy on traversing the route from the base to the source location, as well as clearing the route from obstacles. Let's assume that the agent functions in such a discrete time, where each clock cycle can determine a certain period of its existence. The environment in which the agent operates is determined by a limited amount of non-reproducible resource in the foraging area, as well as many obstacles along the route. The agent can remove these obstacles with some probability, reducing the route length, but at the same time spending some of its energy on cleaning.

The task is to evaluate energy efficiency as a function of the agent energy consumption, which depends on the properties of the medium and the probability that the agent will clear the route.

Let $f(t)$ is the delivered resource, and $C(t)$ is the cost of delivering the resource. The delivered resource is determined by the agent's load capacity and in the simple case $f(t) = f(0) = \text{const}$. All the values used are dimensionless and are defined as the energy received or spent in conventional units, and the time t is discrete. Then the effectiveness of agent $E(t)$ at time t can be determined as follows:

$$E(t) = f(t) - C(t). \tag{1}$$

The cost of delivering the resource $C(t)$ (1) consists of the cost of completing the route $L(t)$, clearing work $W(t)$ and searching for food on the area $C_f(t)$:

$$C(t) = L(t) + W(t) + C_f(t). \tag{2}$$

The cost of completing the route $L(t)$ (2) depends on the distance L_0 between the "base" and the "foraging area" and on the saturation of obstacles:

$$L(t) = L_0 + k_L\rho(t). \tag{3}$$

Here L_0 is an approximately direct route, $L_0 = \text{const}$; $\rho(t)$ is the saturation of obstacles; k_L is the coefficient determining the cost of bypassing the obstacle.

The cost of clearing work $W(t)$ (2) depends on the saturation of obstacles $\rho(t)$ and on the p_w is probability that the agent will remove the obstacle, $p_w = \text{const}$:

$$W(t) = p_w\rho(t). \tag{4}$$

The cost of searching for food $C_f(t)$ (2) is inversely proportional to the amount of food in the area:

$$C_f(t) = k_F/(F(t) + \epsilon). \tag{5}$$

Here k_F is coefficient of the searching cost, $k_F \in \mathbb{R}$, and ϵ is introduced so that when $F(t) = 0$ the costs would be finite, $\epsilon \in \mathcal{R}$, $\epsilon > 0$. The amount of food in the area $F(t)$ (5) decreases with time:

$$F(t) = F_0 - ft. \tag{6}$$

Here F_0 is the initial amount of food on the area. The saturation of obstacles $\rho(t)$ (4) also decreases as the clearing progresses:

$$\rho(t+1) = \rho(t) - k_wW(t) = \rho(t) - k_wp_w\rho(t) = \rho(t)(1 - k_wp_w) \tag{7}$$

or, in the end:

$$\rho(t) = \rho_0(1 - k_wp_w)^t. \tag{8}$$

Here k_w is the coefficient of actions' effectiveness to remove an obstacle. As a result, we get an expression for the agent effectiveness:

$$E(t) = \frac{F_0f - f^2t + f\epsilon - k_F}{F(t) + \epsilon} - L_0 - \rho_0(1 - k_wp_w)^t(k_L + p_w). \tag{9}$$

Obviously, the function determining the amount of resource in the area $F(t)$ must be redefined so that it is bounded from below by zero. If $F(t) = 0$, then the value of $f(t)$ is reset (the agent does not bring anything):

$$F(t) = \max(F_0 - ft, 0), \quad f(t) = \begin{cases} f_0, & \text{if } F(t) - f_0 > 0, \\ 0 & \text{else.} \end{cases} \tag{10}$$

This model allows us to evaluate the effectiveness of the agent's actions during foraging and build a qualitative graph for $E(t)$ (10). Figure 3 shows graphs of $E(t)$ and obstacle saturation $\rho(t)$ (7)

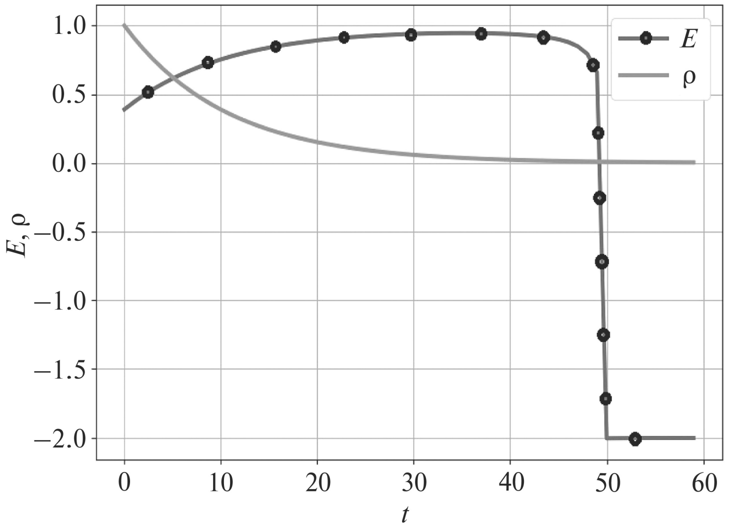

Fig. 3. Graphs of the effectiveness of the agent's actions $E(t)$ and the saturation of obstacles $\rho(t)$ in numerical modeling.

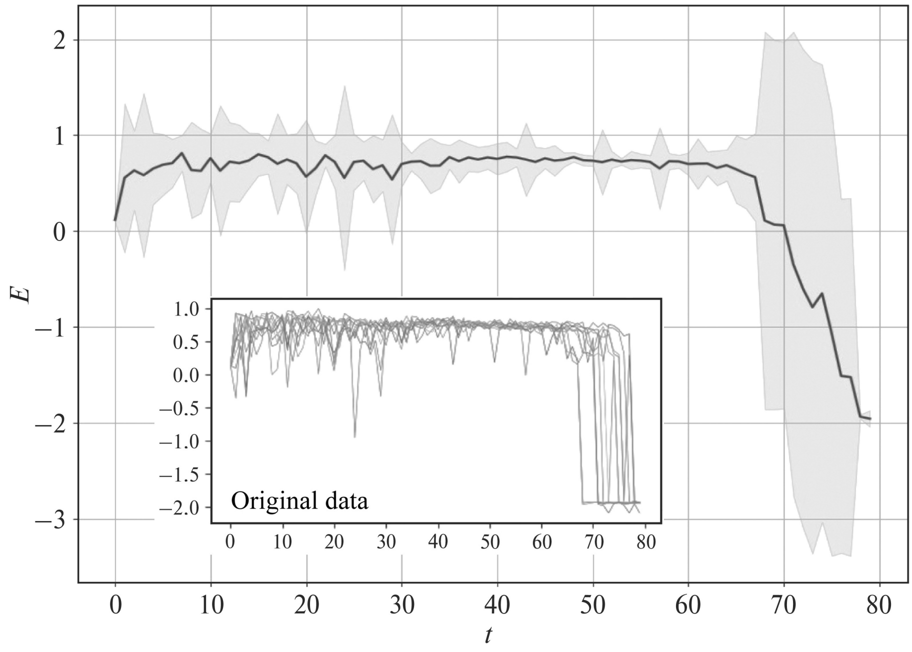

Fig. 4. Graphs of the effectiveness of the agent's actions $E(t)$ in simulation modeling. The average of 10 experiments and the standard deviation.

for the following parameter values: the cost of passing a direct route $L_0 = 1$; the probability that the agent will remove the obstacle $p_w = 0.1$; the cost factor for bypassing the obstacle $k_L = 0.5$; the initial saturation of obstacles $\rho(0) = 1$; initial amount of food in the area $F(0) = 100$; load capacity of the agent $f = 2$; clearing efficiency coefficient $k_w = 0.9$; cost factor for food search $k_F = 1$, $\epsilon = 1$.

Graph $E(t)$ in Fig. 3 shows that the agent's efficiency increases as the route is cleared, reaches a maximum when the number of obstacles decreases below a certain threshold, but then decreases due to a decrease in the amount of food.

Negative values of $E(t)$ on the graph mean that when $F(t) = 0$, the agent only spends its resources while traveling along the route, not replenishing them (works at a loss).

6. SIMULATION MODELING

Simulation modeling was performed using the Kvorum multi-agent modeling system created at the Kurchatov Institute Research Center [33]. The agent moved between two points: from the "nest" to the "foraging area." The time spent on the road was calculated, taking into account the avoidance of obstacles and/or the cost of removing them, and the time spent on the site searching for food. After finding the resource, the agent instantly returned to the "nest" and went back to the foraging area. The experiment ended when the time to search for food exceeded 2000 cycles: then it was believed that the food on the site was over. Figure 4 shows a graph of the $E(t)$ efficiency for a number of simulation experiments. It can be seen from the graph in Fig. 4 that the effectiveness of the agent's actions varies in a similar way to what numerical modeling shows. At first, the effectiveness of the agent's actions increases, since clearing the route leads to a decrease in the time to complete the path. Then comes the stabilization period (35–55 passes, Fig. 4). As the area is depleted, the time to search for food increases, and efficiency decreases.

7. MECHANISMS FOR THE IMPLEMENTATION OF ROUTE ARRANGEMENT OPTIONS

Trampling (natural compaction of the soil). This process is difficult to implement in the laboratory conditions, but in a natural environment it happens naturally when many robots move in the same way. The assessment of the sufficient number of robots is based on an estimate of the number of active foraging ants: for the Formica family of 500 individuals, it ranges from 15 to 45 individuals [34]. Minimum requirements are imposed on the robot: it must be able to navigate by visual landmarks and compass, memorize the route, return to "base" and repeat the route.

Clearing the route (removing obstacles from it). To do this, in addition to the previously listed mechanisms, the robot must be able to: (1) identify obstacles, (2) distinguish movable obstacles from stationary ones, (3) shift or transfer obstacles to the side, (4) return to movement along the route, (5) refine the memorized route, because shifting obstacles changes the configuration of landmarks along the route. In papers [35, 36], a way of navigating by visual landmarks and compass is described, in which the route is remembered approximately. Returning to the route can be implemented as a continuation of the movement "in the same direction," taking into account the landmarks. Therefore, it is necessary to move the obstacle a short distance, sufficient to clear the way and comparable to the size of the robot.

To clear the route, the robot must determine how and when it makes a choice between bypassing and moving an obstacle. After moving the obstacle, the robot must determine further actions: will he follow the route or continue clearing the way.

Surface alignment (horizontal alignment) To do this, the robot must have effectors capable of cutting off the top layer of soil or "laying trenches." This is too strong a requirement, but you can limit yourself to movable elements (obstacles) that you can either drive over or go around them. The robot can shift such elements with an effector in the form of a blade: in this case, clearing the route will also lead to alignment.

The use of improvised material. This is a more difficult option. First, the robot must be able to determine that there is an area in front of it that is inconvenient for movement, for example, a recess. Secondly, he must find an element nearby that can align this area. But this option can be considered as a continuation of the previous one, by analogy with ants that *shift the soil* to level the surface of the trail [23]. And the robot can move obstacles that interfere with the passage to these inconvenient areas. A general list of mechanisms is given in Table. In it, all the previous mechanisms are needed for each next option.

Mechanisms for implementing options for a route arranging by a robot

Options for arranging a route	Mechanisms
1. Trampling	Localization by visual landmarks and compass Memorizing the route Returning to the "base" Repeating the route
2. Clearing the route	Obstacle identification Recognition of movable and stationary obstacles Shifting obstacles to the side
3. Surface alignment	Identification of an obstacle that can be skirted from the side or run over
4. The use of improvised material	Identification of an inconvenient area where an obstacle can be moved

8. CONCLUSION

This paper has two aspects — technical and methodological. The first aspect is concerning the behavior modeling and is as follows. The reasoning and simulation results above confirm the assumption that in fact there are no roads in the world of ants in the sense that man puts into this concept. There are only routes and directions of movement, and the route arrangement in order to reduce energy costs in a simple case can be carried out without organizing joint purposeful activities of many agents (robots). Thus, we have shown that without creating new entities, without involving any artificial structures, we can get the same result and observe the same phenomenon, which biologists call "ant roads." Formally, this means the absence of the "road" entity in the agent's world model, which entails the absence of the need to create behavioral procedures corresponding to this sign, representation/recognition, etc. This greatly simplifies the solution of the problem.

The second aspect is methodological. It emphasizes that the attitude towards bio-inspired models should be critical and constructive. Let's go back to the title of the paper and summarize what the "pitfalls" of bio-inspired models are.

1. Superficial analogies in bio-inspired behaviors are a dangerous thing. "Nature-inspired" models often have nothing to do with what is available in nature. The danger lies in the fact that such a superficial view ignores the mechanisms underlying a particular behavior. As a result, specific models are obtained that reflect only the external, phenomenological aspects of natural phenomena.
2. The identification and implementation of basic behavioral mechanisms has purely practical aspects. This saves effort when developing systems, makes it possible to combine these basic mechanisms and provides flexibility. An example of this approach is the paradigm of social behavior models.
3. Real biological models and descriptions of phenomena also require a critical attitude. The point is that biologists and technical specialists use different concepts. The latter should consider important the essence of the phenomenon, as well as its constituent elements and the causal relationships between them. Without this, it is unclear what needs to be modeled. An example of this phenomenon is ant roads, which were discussed in this paper.

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