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Bio-inspired approach to robot orientation based on navigation mechanisms of some ant species

Биоинспирированный подход к ориентации роботов на основе механизмов навигации некоторых видов муравьёв

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Ключевые слова: ориентация муравьёв, модели социального поведения, автономные мобильные роботы, задача фуражировки.

Abstract. The paper describes a bio-inspired mechanism for orientation and navigation of mobile robots based on navigation elements of some ant species, namely: *Camponotus pennsylvanicus* (De Geer, 1773), *Formica subsericea* Say, 1836, *F. rufa* Linnaeus, 1761, *Cataglyphis fortis* (Forel, 1902), *Melophorus bagoti* Lubbock, 1883 and *Myrmecia pyriformis* Smith, 1858. The path is represented as a sequence of scenes formed by visual landmarks. The description of the path includes compass data and a time component. The method allows the robot to memorise the path and return to the departure point. The results of simulation modelling for solving the single foraging problem are presented. The experiments on real mobile robots are described.

Резюме. В работе описывается биоинспирированный механизм ориентации и навигации мобильных роботов, подобный тому, который используют некоторые виды муравьёв: *Camponotus pennsylvanicus* (De Geer, 1773), *Formica subsericea* Say, 1836, *F. rufa* Linnaeus, 1761, *Cataglyphis fortis* (Forel, 1902), *Melophorus bagoti* Lubbock, 1883 и *Myrmecia pyriformis* Smith, 1858. Метод базируется на представлении пути как последовательности сцен, образуемых визуальными ориентирами, с учётом показаний компаса и временнóй составляющей. Метод позволяет роботу запомнить путь и вернуться в точку отправления. Приведены результаты имитационного моделирования для решения задачи одиночной фуражировки, описаны натурные эксперименты на реальных мобильных роботах.

Introduction

The basic principle of group robotics is the joint solution of tasks by a group of relatively simple robots. A group can perform tasks that an individual robot cannot perform. Bio-inspired models and methods have long been used to solve the problems of group robotics. One of the most promising approaches in this area is the application of social behavior models (SBM) [Karpov et al., 2019]. The basis of this approach is the study of behavioral models of social insects, primarily ants, the formalization of these models, and their use to organize a robot group. The SBM paradigm assumes that any complex social behavior or phenomenon consists of a small number of basic mechanisms. To model behavior, it is necessary to understand what basic elements it includes, and use a combination of basic mechanisms to implement any type of behavior. This makes it possible not to create specific models and methods for solving individual tasks of group robotics, but to use a generalized approach.

The SBM approach includes a number of models, methods, and algorithms that have been developed and are already being used for group robotics. They are based on the results of a study of behavior of ants as social animals. In particular, a behavior model was created for modelling group foraging [Malyshev, Burgov, 2020]; a model of aggressive behavior for distributing of «foraging areas» between robots [Karpova, Karpov, 2018]; an imitative behavior model [Karpov, 2019]; and a mechanism of implicit communication [Vorobiev, 2024], etc.

In order to verify the applicability of SBM, some complex task is needed, which can be solved using this approach. Foraging can be considered as such a task. Foraging will be understood as the search and collection of resources by a robot group with the subsequent delivery to the resource collection point, i.e., to the «base» [Malyshev, Burgov, 2020]. This is a complex task in nature because the ant colony also explores and monitors the territory during foraging, laying the basic framework for the protection of the territory [Zakharov, 1991; Fedoseeva, 2015; Malyshev, Burgov, 2020]. The tasks of collecting resources or information, exploration, monitoring, and protection of the territory are among the tasks solved in the field of group robotics [Faria Dias et al., 2021].

The technological approach to the description of group foraging by *Myrmica rubra* (Linnaeus, 1758) is well suited as a basis for its modelling [Fedoseeva, 2015]. This approach identifies several stages of foraging.

1. Exploration: a scattered survey of the foraging area by a few scouts.

2. Activation: a procedure for stimulation of nestmates by scouts.

3. Guidance: mass exit of workers from the nest to the new food source.

4. Transportation: transferring food into the nest.
5. Saturation: a decrease in foraging activity of ant colony.

It seems that with the developed basis of behavioral models, there is nothing difficult in modelling the foraging system. The foraging process itself is well described, it includes the models and mechanisms previously developed and implemented within SBM for simpler tasks [Malyshev, Burgov, 2020; Karpova, 2016]. Also, it is enough to take these mechanisms, combine them, and obtain the desired result. However, it turns out that the most difficult thing here is to solve the basic problem of orientation and navigation with memorization and using of the route [Karpova, 2022a], as well as with the possibility of transferring the route description from one individual to another [Ryabko, Reznikova, 2009]. Some of existing models (see the review by I.P. Karpov [Karpova, 2022b]) allow the robot to memorize the route image, but these models do not imply the transfer of the route image between robots, at least due to the large volume of such an image.

The aim of the study is to create a mechanism for the orientation and navigation of a real robot at the testing ground, and in the future — in a real environment. The basis of this method should be mechanisms similar to those used by ants. The method must meet the following requirements: (i) the route description should take up as little memory as possible; (ii) the robot may have limited sensory capabilities; (iii) work should be carried out in conditions of low positioning accuracy, with identical landmarks, and in situations where no landmark is visible.

To achieve this goal, the following tasks must be solved: (i) to study the mechanisms of ant orientation and navigation; (ii) to create a model of the selected mechanism (at the behavioral level, but as close as possible to the original); (iii) to implement this model and test its performance using simulation and real robots.

Methods and approaches

Terminology

The object of the study is an artificial autonomous agent, which is operating in a virtual or real environment and simulating the behavior of a living organism [Wilson, 1987]. Therefore, the term «animat» is more often used in the paper. However, if describing real experiments, the term «robot» is used.

In this case, orientation means determining one's location relative to objects known to the animat or robot. Navigation refers to the ability of an animat or robot to choose the movement direction and memorize its route, return to the departure point and, if necessary, repeat this route. This is very different from what is called navigation in robotics and usually involves planning the optimal route. However, such navigation requires the presence or construction of a map, and it is assumed that ants do not build a map [Wehner et al., 2023].

Animat's localization and navigation

To implement foraging, the animat must be able to navigate, i.e., memorize the route while driving, return to the «nest» (to the «base»), and repeat the route. It should also be able to transmit the route description to other specimens so that they can take this route. This orientation method should be based on mechanisms similar to those used by ants. It should be noted that in this study, the mechanism of ant's navigation is considered simplistically and from an external, phenomenological point of view. The author does not try to propose an imitation model based on morphological and anatomical features of ants.

The ways in which ants navigate, locate, and transmit signals differ from species to species. The pheromone trail in a number of robotic works is often considered as the main way of ant's orientation in the foraging area [Dorigo, Blum, 2005]. However, the analogues of this mechanism are very complex and time-consuming to use on real robots. In addition, this mechanism plays an important role in the mobilization and organization of traffic on roads (in a number of ant species), and exploration is carried out without it. This paper focuses on the basic principles of orientation of single foragers (or those operating in small groups) of herpetobiont species:

1. Many ants species use the following methods of orientation and navigation when moving on the ground: celestial compass orientation (*Camponotus pennsylvanicus* (De Geer, 1773) and Formica subsericea Say, 1836 [Klotz, 1987]; *F. rufa* Linnaeus, 1761 [Jander, 1957]; *Myrmecia pyriformis* Smith, 1858 [Reid et al., 2011]);); odometric information («pedometer») (*Cataglyphis fortis* (Forel, 1902) [Wittlinger et al., 2006]; *Melophorus bagoti* Lubbock, 1883 [Schwarz, Cheng, 2011]); path integration system (*C. fortis* [Müller, Wehner, 1988]; *M. bagoti* [Narendra, 2007]).

2. «Compass» and «pedometer» accumulate errors; so many ants also use visual landmarks to navigate (*F. rufa* [Graham et al., 2003]; *C. pennsylvanicus* и *F. subsericea* [Klotz, 1987]). Moreover, for experienced foragers, the information provided by the landmarks dominates the information from the path integration system in case of their conflict [Wystrach, Graham, 2012].

3. Ants of some species behave as if they took two-dimensional views («snapshots») of the landmark scenes seen from particular vantage points, stored these views, and later when again approaching the goal, in particular when entering the area surrounding the goal, compared the stored views with the current ones and tried to occupy the same position [Wehner, 2009]. We will refer to such snapshots as scenes. Observing the behavior of an ant when memorizing a scene can be interpreted as follows: it examines the landmarks that make it up, selects the main one, and then walks around it to the right or left. This assumption is confirmed by the fact that when re-traversing this route, the ant tends to bypass a familiar landmark from the same side, even if the landmark was moved to the left or right of the initial position [Wystrach et al., 2011]. Ants do not repeat the route with high ac-

curacy, and the route description defines a visual corridor rather than a narrow road [Baddeley et al., 2012].

4. Probably, ants of some species distinguish between two types of landmarks, which can be called local and waypoints [Cruse, Wehner, 2011]. The first ones are located near the nest and near permanent feeding areas and the second ones are on the way to the feeding area or back. Detecting a waypoint causes the ant to turn at the right angle and keep moving. The discovery of a local landmark triggers a systematic search procedure: an ant associates a local landmark with a nest or food source, and the worker begins to methodically circle around this place until he finds what he is looking for.

5. If, while traveling along the route, a passive forager sees the desired object (food or other resource), he can stop moving along the route and head to the object to take it and transfer it to the nest. Thus, the route may not be completed to the end.

The task of animat's orientation during foraging includes three stages, namely to find the desired resource (food), return to the departure point (to the «nest») and, if necessary, repeat this path. The proposed orientation and navigation mechanism uses only visual landmarks and a compass. Therefore, ants of the genera Formica and Cataglyphis can be taken as the main model objects. It is believed that in the process of searching for food, in ants of the genus Formica [Dlussky, 1967], the scout memorizes position relative to the sun, the visual landmarks it passes by, and the approximate distance to landmarks. This allows him to return back to the nest and transmit information about the route to foragers so that they can independently reach this food [Zakharov et al., 2013; Reznikova, 2020].

The route can be represented as a sequence of segments on which the animat moves in a straight line (Fig. 1).

At the beginning of each segment, the animat-scout memorizes the scene, selects the main landmark (ML) and the walking direction relative to this landmark. If the animat does not see any landmarks, then it returns to the «base» (such a search is unsuccessful). A scene is a set of landmarks that are simultaneously visible to the animat, taking into account their relative location and time component. For each scene, the animat memorizes

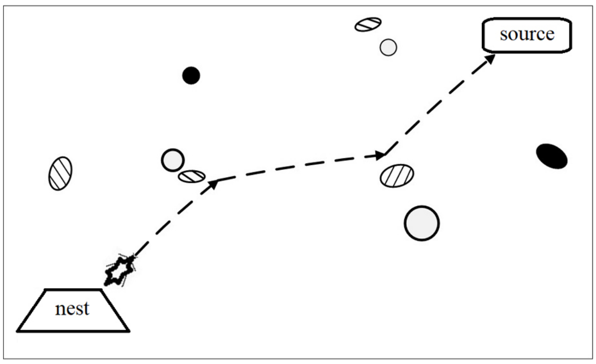


Fig. 1. Example of an animat's route from the «nest» to the food source.
Рис. 1. Пример маршрута анимата от «гнезда» до искомого ресурса.

compass direction and the number of «steps» it took on this section of the path before moving on to the next segment. For the animat, the scene is not just a set of visible landmarks and the relationships between them. The scene also determines the animat's behavior and changes its internal state.

A celestial compass is not used in this simplified model. Instead, an ordinary magnetic compass is used, so it is not necessary to take into account the correction for a change in the position of the animat relative to the light source. Memorizing the number of «steps» does not mean using odometry, because this information is not converted into the distance traveled, but is considered as the number of cycles, i.e., the time component. Thus, the concept of time is introduced into the model, which is tied not so much to the clock cycles (the animat's steps), but to a change in its state relative to the environment, i.e., the completion of one segment of the path and transition to the next. The principle of forming a route description is based on the fact that the ant scout remembers the path approximately, and the forager ant repeats this path, but not exactly.

The scout's actions algorithm is shown below.

1. The animat-scout starts the journey from the «nest», memorizing its direction by compass. It must see at least one landmark in order to remember the scene and start moving.

2. From the visible landmarks, the animat chooses the main landmark, the direction of its circumvention (left or right), and memorizes the scene as an element of the route.

3. If, during the movement, the animat sees the desired resource («food»), it memorizes the current scene as an element of the route, approaches the resource, takes part of it and proceeds to point 6.

4. The animat makes a detour around the main landmark of the scene (left or right).

5. If, after completing the bypass of the main landmark, it sees at least one new landmark, it proceeds to point 2. If it does not see any, it considers that the path has been completed to no avail and proceeds to point 6.

6. The animat transforms the description of the route into a return trip and returns to the «nest». If the «food» has been found, the scout either mobilizes passive foragers and leads them, or gives them the route description to the «food» so that they can get there on their own. If the «food» has not been found, then the scout goes in search again, slightly changing the direction of his movement.

If the animat-scout loses its orientation when returning to the «nest», i.e. it does not see the necessary main landmark and cannot recognize the scene, then the animat continues to search for the «nest», moving in the direction where it is presumably located.

The animat-forager receives a description of the route and acts according to a similar algorithm. However, does not look for a new landmark, but compares scenes from the route with what it sees around. The forager also memorizes the scenes while driving along the route, and makes up its own route description. If the forager loses its orientation in the process of moving to the resource, it transforms the route description into a return path and follows it to the «nest».

To implement this behavior, an animat must be able to move and have a compass and a locator that implements a visual perception system. It must also have memory to store the route. The animat's world can be divided into cells. The cell size is determined by the characteristic linear size of the animat or real robot. Such dimensionless units are convenient for describing the animat behavior and allow us to abstract from the actual physical dimensions. Using the locator, the animat recognizes objects that are in its field of view, but instead of numerical physical quantities, it operates with the concepts of «the object is close to the left» or «far to the right-ahead» (Fig. 2).

The technical implementation of this mechanism is provided by a route description model, an algorithm for converting a direct route into a reverse route, and the interpretation rules that allow us to repeat the route according to its description. The model includes the concept of a landmark as a compact group of objects located close to each other. An object is some visual element of the environment that an animat can recognize using a visual perception system.

The objects and landmarks on the testing ground are not unique and can be repeated, so the animat compares the scenes. The proposed procedure for comparing scenes is based on comparing the main landmark of the scene and its context, i.e., landmarks to the left and right of the main one. The similarity of landmarks is defined as the inverse of the distance between them in some metric space, which is formed by bipolar scales for the objects attributes. Linear convolution of criteria is used to determine the degree of similarity of scenes. The method is described in more detail by I. Karpova [Karpova, 2022b].

The general principle of converting a direct route description into a reverse one is as follows: the reverse route consists of the same scenes as the direct route, but in reverse order. For the direct route, the endpoint is the desired resource, and for the reverse — the «nest». The landmarks of each scene are mirrored from left to right, and the direction of movement is reversed (approximately 180° by compass). Short scenes in which the animat spent less than 50 clock cycles are removed from the route description. The threshold of 50 clock cycles is set experimentally. This increases the stability of animat and robot on the route.

The present work is registered in ZooBank (www.zoobank.org) under LSID urn:lsid:zoobank.org:pub:78916920-EECC-46B8-8F46-1A906BFBF70B

Results

Simulation modelling

The experiments on modelling single foraging were carried out using the Kvorum modelling system [Karpov et al., 2018]. The option of transferring the route description from the scout to the forager was not considered,

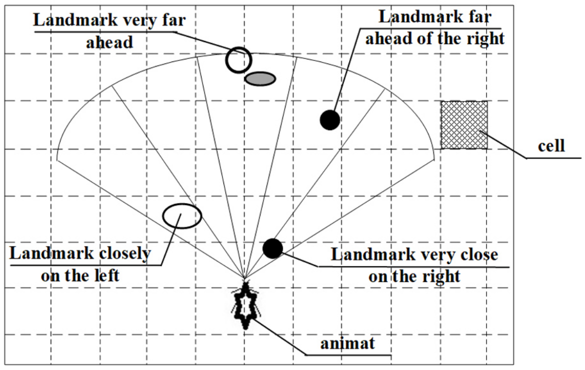


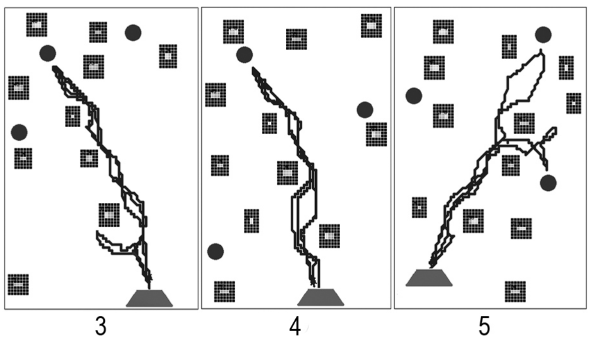
Fig. 2. Animat's «world»: field of view, directions and distances.

Рис. 2. «Мир» анимата: область видимости, направления и расстояния.

because it is not indicative at the level of simulation modelling. Animats as software objects are completely identical; the transfer of the route description is carried out by simple copying. Therefore, the forager repeats the path in the same way as the scout.

Figures 3–5 show examples of running a simulation program. Figures 3–5 contain an edited copy of the computer screen on which the program visualizes the testing ground and the animat movement during the experiment. Rectangles represent landmarks, a trapezoid is a «nest», the circle represents the desired resource; the lines reflect the paths along which the animat moved.

The testing ground is an area of 200×200 cells; the simulation time is 20,000 clock cycles for each experiment. Figures 3–5 show only part of the testing ground to save space. Various configurations of landmarks on the testing ground were investigated. There were five runs of the simulation program on each configuration.



Figs 3–5. Examples of simulation results. 3 — the animat returns to the «nest» and begins a new search after orientation failure; 4 — the animat successfully searches for a resource with a return to the "nest" and repeats the route again; 5 — the animat fails to follow the route due to similar landmarks and comes to another resource. Designations: Rectangles represent landmarks, trapezoid is a «nest», circle is a food source; lines are the path along which the animat moved.

Рис. 3–5. Примеры результатов моделирования. 3 — возвращение анимата в «гнездо» и начало нового поиска после сбоя ориентировки; 4 — успешный поиск ресурса аниматом с возвращением в «гнездо» и повторением маршрута снова; 5 — ссбой повторения маршрута из-за похожих ориентиров и нахождение аниматом другого ресурса. Обозначения: прямоугольники — ориентиры, трапеция — «гнездо», круг — источник пищи, линии — путь, по которому двигался анимат.

Table 1. Statistics of simulation results
Таблица 1. Статистика результатов моделирования

Number of experiments	Description of the animat's behavior	Number of successful/ unsuccessful returns	Number of experiments, %
35	The animat found a source, returned, and repeated this route	70/0	70
3	The animat found a source (not immediately), returned, and repeated this route	12/0	6
5	The animat found the source, returned, but could not repeat this route (did not find the source, did not return to the "base")	5/5	10
2	The animat found the source, returned, did not find it for the second and subsequent times, but returned to the "base"	7/2	4
5	The animat went for the source many times, did not find it, but returned to the «base»	87/2	10

At the beginning of the experiment, the animat has a certain orientation (for example, 90° relative to the testing ground), and this direction changed from 70° to 110° in increments of 10° for different launches of the program. A total of fifty experiments were conducted.

At the beginning of each experiment, the animat left the «nest» to search for a resource whose location was unknown, then returned to the «nest» and repeated this path himself along the memorized route (two round trips in one program run). If during the search the animat stopped seeing landmarks, it returned to the «nest» and started the search again, changing the initial direction of movement (Figs 3–5). In most experiments, the animat found a resource, returned to the «nest», and successfully repeated this path again (Fig. 6). Sometimes the animat lost its way because of the same landmarks (similar scenes) and, when repeating the path, came to another resource (Fig. 5) or returned to the «nest» without «food». The general statistics of simulation results for fifty experiments are shown in Table 1.

If experiments in which the animat reached the same resource twice are considered completely successful, then there were 38 successful outcomes. This is 84 % of the 45 experiments in which the configuration of landmarks allowed the animat to solve the problem of searching for a resource. If we do not take into account the experiments in which the animat returned all the time due to the lack of landmarks, then the animat did not return on seven occasions from the 101 round trips. This is approximately 93 % of successful passes or 95 % of successful returns to the «nest» of the total number of passes.

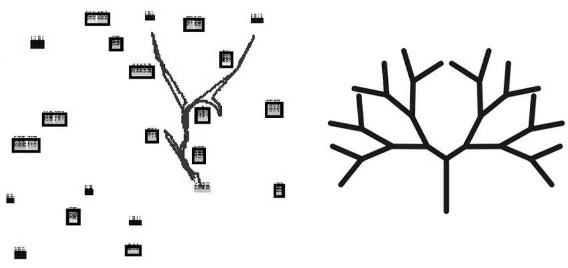
Experiments with real robots

An important result of the research was real experiments that were conducted on mobile mini-robots developed at the Robotics Laboratory of the Kurchatov Institute Research Center. The mini-robot is a mobile platform with a differential drive, equipped with rangefinders, a gyrocompass, a camera, and an on-board Raspberry Pi 4 computer. The experimental complex includes a mobile robot, a remote control computer, and an indoor testing ground with landmarks. Each object included in the landmark is marked with an ArUco marker for stable recognition (Fig. 6).

Fig. 6. The indoor testing ground for experiments with real robots.
Рис. 6. Полигон для проведения экспериментов с реальными роботами.

The on-board computer provides motor functions and data processing from the camera. The camera implements a visual perception system and is the main source of information about the objects observed by the robot, i.e., landmarks with ArUco markers. The program on the control computer receives data from the camera and sensors of the robot, processes them, and sends commands to the robot, specifying its movement. Thus, the program controls the robot behavior at the testing ground during foraging.

The robot was controlled by the same program that carried out simulation experiments and statistics collection. During field experiments, the robot behaved similarly to an animat in computational experiments. It started moving from a «base», i.e., a landmark with an ArUco marker number 2. The robot moved between landmarks in search of a «resource», memorizing the route. The resource is an ArUco marker number 1. After finding it, the robot returned to the «base» and repeated the route to the «resource» and back. The success rate of finding and returning a robot is about 5 % worse than that of an animat in simulation. This can be explained by the errors of real sensors compared to virtual ones. Nevertheless, the results of real experiments confirm the efficiency of the created orientation method and its adequacy to real conditions.



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Figs 7–8. Conditions of the experiments. 7 — a search on the testing ground in the Kvorum system; 8 — the maze «binary tree» in experiments with ants [Ryabko, Reznikova, 2009].

Рис. 7–8. Условия проведения экспериментов. 7 — поиск на полигоне в системе Kvorum; 8 — схема установки в опытах с муравьями [Ryabko, Reznikova, 2009].

Discussion

It is of great interest to compare the navigation efficiency of animat and *Formica* and *Cataglyphis*, but there are some problems here. In field observations, such statistics, as far as the author knows, are not calculated, because this is an extremely time-consuming process, and it is possible to compare indicators only if statistically reliable data are available. If we talk about experiments at the landfill, then the conditions for their conduct are closer to the conditions of laboratory experiments with artificially created infrastructure than to observations in wildlife. This primarily involves landmarks marked with special ArUco markers for more reliable recognition and identification. If compared with laboratory experiments [Ryabko, Reznikova, 2009], then the conditions for their conduct differ significantly from those that were modeled in this research. In this work, the animat searches for a resource on the plane (Fig. 7 — raw image of the model testing ground). In laboratory experiments, ants search for food in a maze called «binary tree» (Fig. 8).

On the one hand, there is a certain similarity. When searching on the testing ground, the path can also be represented as a sequence of segments. On the other hand, B. Ryabko and Zh. Reznikova evaluated in experiments for the accuracy of following the route [Ryabko, Reznikova, 2009], the information about which was transmitted by a scout to a passive forager. There are several fundamental differences between ants and animats. First, animats and ants have different ways of representing the data. There is little information on the exchange of data between ants, but it is likely that the ants transmit some conditional signals to each other. Animats, on the other hand, exchange associative sequences of landmarks along the route that they have memorized. Secondly, there is an assumption that scouts remember the path better and keep the memory of it longer than mobilized foragers [Atsarkina et al., 2014]. Animats are identical in their structure and capabilities, and there are no fundamental morphological differences between robots. Therefore, with an error-free transmission of the route description, the forager will repeat the path in the same way as the scout. Thirdly, ants may have errors when transmitting data.

Adding an error when transferring data between animats is pointless, because it is impossible to establish a correspondence with animat errors and ant errors. Errors in data transmission between real robots are inevitable due to equipment errors, induced noise, etc., but any analogies with nature here can also be only superficial. Based on all of the above, it is not possible to make a quantitative comparison of the efficiency of navigation in ants and in artificial agents.

Conclusion

This paper describes the basic principles of a mechanism that mimics the navigational behavior of some species of herpetobiont ants, which is demonstrated during foraging. This behavior was considered simplistically and from an external, phenomenological point of view. The results showed that at this level it can be done with fairly limited means.

When simulating foraging for robots, the significant difficulty is returning to the departure point. The main task of the current stage of the study was to create an algorithm for converting a direct route into a reverse one, and this task was solved. The experiments carried out confirmed the operability of the proposed mechanism. In the future, it is planned to switch from single foraging to collective foraging, as well as apply this approach to solving other tasks (monitoring, patrolling the territory, etc.).

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