Redistributing Animats between Groups

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Abstract. The paper refers to the research direction in which models of social behavior are the methodological basis for the functioning of robot (animat) groups. The purpose of this study is to implement a complex regulatory behavior of animat groups using previously created models and methods. The applicability of this approach is demonstrated by the task of redistributing animats between groups. To accomplish this, the paper proposes to implement a mechanism similar to the phenomenon of slavery that is characteristic of some species of ants. Slavery is a form of social parasitism and can be considered as a method for the redistribution of individuals between families (groups). The paper describes different types of slavery and the behavior of slave owners and slaves among species of ants. The main processes that make up this behavior are: exploring territory, organization of raids, seizure of slaves and their transfer to the slave-makers' nest, and slaves' adaptation in the new nest. The thesis proposes that this behavior is based on the "friend-alien" identification and is an evolutionary development of food and territorial behavior. The paper describes previously created methods, models, and mechanisms for implementing similar forms of animats' behavior: foraging, pack hunting, territory defense, and domination based on aggression. A method for identifying an animat and determining its internal state, which is necessary for organizing the interaction of animats, is proposed. Finally, the paper describes experiments confirming the applicability of the proposed method.

Keywords: Group Robotics, Social Behavior Models, Ant Slave-Making, Foraging Task, Aggressive Behavior.

1 Introduction

Consider the situation in group robotics, in which the robots are divided into groups. Each group is relatively stable and is designed, for example, to solve a separate problem. In this case, it may be necessary to redistribute robots between groups, if some task becomes more complicated and requires more "working hands" to solve it. It is necessary to develop a mechanism that would allow a fairly natural way, without the use of special techniques, to redistribute robots between groups.

Such stable formations are observed in nature—in particular, in social and eusocial animals—and are based on models of social behavior [1]. The most prominent representatives of eusocial animals are ants. Many researchers in the field of group robotics use them as a "role model" [2, 3].

Let us consider what mechanisms for redistributing individuals between social groups exist in ants. Families of most species of ants are fairly stable. Family size usually changes due to reproduction and natural loss. As a result, there may be a separation of the family when an anthill is overpopulated or the two families are united into one after a mass death of individuals. It is also possible to capture alien ants and their brood during wars [4]; association of families of different species as a result of migration [5]. However, we are more interested in the phenomenon of slavery.

Slavery in ants is a form of social parasitism. Slave-making ants raid nests of other ant species, capture the developing offspring, and rear them to slave workers [6]. Subsequently, the captured individuals (the so-called slaves) are integrated into a foreign colony. The mobilization of alien individuals allows one to free oneself from the nesting activity inside and to increase the number of foragers. Accordingly, the increase in the number of workers is provided by the energy costs of another nest.

There are facultative and obligate slave-making ant species. Facultative slave-makers are able to forage, nurse their brood, and construct their nests like free-living ants, hence colonies without slaves are often found. For obligate slave-making species, the presence of slaves is a prerequisite for the survival of the species because such species are not able to perform certain vital functions (for example, caring for the brood). Raids and the integration of captured individuals in a new family can be viewed as a mechanism for the redistribution of individuals between groups.

The main idea of the proposed approach is to implement the redistribution of robots between groups without additional mechanisms and rules. We will try to limit ourselves to the models and mechanisms that were developed earlier in the application of social behavior models to solving group robotics problems. First, it is necessary to examine in detail the phenomenon of slavery and the behavior models on which slavery in ants is based.

The purpose of this study is to implement complex regulatory behavior of animats using previously created models, methods, and mechanisms. An animat is an artificial agent that acts autonomously in a real or virtual environment and simulates the behavior of a living organism. The problem to be solved is the following. How can animats belonging to one group recruit individuals from another group for the redistribution of forces?

2 The Behavior of Slaves and Slave-Makers

Ants of an obligate slave-making species periodically organize raids on the neighboring nests of the host species. In the process of raids, they seize brood or young workers and bring them to their own nest. Only those individuals who do not resist the invaders are subject to capture (resisting individuals are killed or expelled). Here it is necessary to mention the well-known phenomenon of the increasing aggressiveness of ants with age [7]. Consequently, young workers have lower aggressiveness than those who go on the raid.

It is well known that ants recognize each other by odor. All ants in the nest have a certain odor and perceive each other as “nestmates.” Ants from other nests are “aliens,” they have a different odor. In the new nest, captured young workers and individuals released from the brood quickly acquire the odor characteristic of this nest. Slave-making workers begin to perceive them as their own nestmates. In the beginning, the slaves are mainly engaged in the intra-nesting activity. As they grow older, they can participate in other work, including new raids. For example, according to Mori, Grasso, and Le Moli [8], among the workers of the Formica sanguinea nest there was no division of labor between slaves and slave-maker workers because the same ants were raiders during the campaign for slaves and foragers during the foraging.

Now we will consider what mechanisms this behavior is based on.

The evolutionary basis for raids is foraging [9]. Foraging is part of eating behavior. Scout ants mine protein foods. In search of food, the scout surveys his sector of the territory around the nest, memorizing the route. If the scout has discovered the food and cannot transfer it himself, he will return to his nest. He mobilizes other ants (passive foragers) near the nest.

Facultative slave-making species represent a parasitic group between free-living species, on the one hand, and obligate species. According to the observations of Mori, Grasso, and Le Moli [8], scouts of obligatory slave-makers seek only slave colonies, while scouts of optional slave-makers (in particular, Formica sanguinea) seek both food and nests of potential slaves. This fact confirms the assumption that the purpose of scouting ants was to search for food. And only with the advent of slavery did the intelligence officers shift to the search for foreign nests as a source of resources.

The raid is organized like any other campaign: to go to war, to defend the territory, to eat, and so on. Before the raid, scouts survey a certain sector. They return to the nest if they discover the desired resource or reveal a situation that requires coordinated actions of many individuals [10]. Then they mobilize other ants using recruitment signals and lead them to the place where the problem arose or the resource was discovered. A resource, in general, can be not only food but also any other object (or subject) that the nest needs. In particular, representatives of another nest as free labor can be a resource.

In this way, initiating a raid is a simple search for a resource. Slaves for obligate slave-makers are a prerequisite for the survival of the species, so they can be considered as a resource. Raids occur periodically: when there is a shortage of manpower, hunger, cold, and other inconveniences. For our task, the reason for the organization of the raid in the first place is the group’s need for additional labor. The causes for the emergence of this need in our case are insignificant.

Scouts lead mobilized passive foragers to an alien nest, which is a place of concentration of potential slaves. Scouts are dominant and give a recruitment signal, so passive foragers follow them. In addition, cohesion plays a significant role in coordinating group activities [11]. Near the attacked nest, fights take place between the raiders and local residents. There are two mechanisms here—aggression and imitative behavior [12]. On the one hand, when ants meet with aliens who are competitors, they have an aggressive reaction. The outcome of the confrontation depends primarily on the degree of aggressiveness of individuals and on the ratio of “nestmates” and “aliens.” On the other hand, coordinated behavior of ants is usually achieved through a group hierarchy and mass imitation by the majority of individuals of activator ants.

During raids, individuals of the slave species are captured, destroyed, or escape [10]. There are also no specific rules here, only the rules for the interaction of ants with representatives of other species (or other nests) [7]. When two representatives of different species (or nests) are encountered, the following situations are possible:

1. The ants ignore each other.
2. One ant behaves aggressively, the other does not (remains passive).
3. Both ants behave aggressively toward each other.

Aggressors cannot be passive, so the first option is not considered. In the second case, the aggressor can grab a passive individual, which folds up as a “suitcase” and allows itself to be carried. The third option leads to a fight, as a result of which one individual can be killed or damaged.

Captured young workers adapt to someone else’s nest. The socialization of a slave is based on the following elements of behavior [6]:

- Nestmates do not kill the slave because he acquired the necessary odor and partially adopted the behavior patterns of the slave-makers. He has lower aggressiveness, therefore he does not cause an aggressive reaction in the slave-makers.
- The slave submits to the slave-makers because they are stronger and more numerous. Once in a strange nest, the slave cannot show the aggression that the inhabitants of the nest cause in him: there are too many of them, he will simply die. The threat turns into danger, and the need for self-preservation drives the slave to demonstrate submission (there is nowhere to run). On this basis, the general behavior of a slave is passive.
- The slave works because it fits his behavior program, individual needs, and the like.
- The slave can change the sphere of activity: as he grows, his aggressiveness increases with age, and there is a need to perform more active types of work than those inside the nest.

In the new nest, the slaves do the same work that they would have done in their nest. This can be explained by the fact that the slave is placed in an environment that is not very different from his own nest, and he does the same work that he would do in his nest. For him, after moving to a new nest, almost nothing changes, only the freedom to choose a profession (type of activity) is limited. On the other hand, even in slave-free nests, young workers are subordinate to senior and experienced workers. Seniors can, for example, take young workers outside to do a specific job. Or, they may drive young workers into the nest if there are too many workers outside and they interfere with each other. Therefore, the slave “can consider” that he continues to live and work as before, without realizing his “slave position.”

Next, we consider how these mechanisms and behaviors were implemented in earlier studies in the field of group robotics.

3 Models and Mechanisms for the Implementation of Certain Types of Behavior

3.1 Previously Created Models and Methods

Animat Control System. Karpov [13] proposed the architecture of the need-emotional control system for the animat. In this system, emotions determine the overall assessment of the current situation and are the basis for controlling the behavior of the animat. This approach is based on the need-information theory of emotions P. Simonov [14].

In accordance with Simonov's theory, emotions are an assessment of the value of the current need and the possibility of satisfying it. The brain evaluates this possibility based on genetic predisposition and previously obtained individual life experience. This can be expressed as follows [13]:

$$E=f(N, p(I_{need}, I_{has})), \tag{1}$$

where E is the emotion (its force, quality, and sign); N is the force and quality of the current need; $\boldsymbol{p}(I_{need}, I_{has})$ is the estimate of the possibility of satisfying the need using the inherent and gained life experience; I_{need} is the information about the method to satisfy the need; and I_{has} is information about the means, resources, and time the subject has presently at its disposal. The difference between the need and possibilities of their satisfaction determines the emotional estimate of the current situation. If we have some needs and the possibilities of satisfying them are sufficient, then we have a positive emotional estimate. Otherwise, the emotions are negative.

The condition for the initiation of any action is negative emotions associated with unrealized needs. In the robot control system, the state of each action block is characterized by its private emotion E_i. The condition for choosing an action C_a is determined by the emotional state of the agent (animat):

$$C_a=C_a(E),\ E=\{E_i\} \tag{2}$$

The set of behavior rules is represented in MYCIN-like form, that is, in the form of productions with confidence coefficients

$$R_n : Cond_1 \wedge \ldots \wedge Cond_i \rightarrow (a_n) \tag{3}$$

where i=1,…,m and m is the number of actions performed by the robot. For example, the rule "eat" can be represented as

IF "There is need in food" (N_{food}) & "I'm hungry" (S_{hungry}) & "I see food" (S_{food}), THEN "Eat" (a_{eat}),

where N_{food}, S_{hungry} and S_{food} are the confidence coefficients and the coefficient a_{eat} in the rule is determined by $a_{eat} = \min(N_{food}, S_{hungry}, S_{food})$.

In this way, all the confidence coefficients a_i (i=1,…,m) for all rules can be determined at the current point in time, where a_i is the magnitude of the predicted necessity of the action I_{need}. However, the actual coefficient a_i^{actual} in the rule may be different from a_i because the robot can perform only one action at a time (this is our assumption). Thus, we can find the emotional estimate for all actions a_i:

$$E_i=N_i(a_i - a_i^{actual}) \quad (4)$$

The effect of emotions on the execution of an action is implemented as a positive feedback between the output signal (current action) and the behavior rules. A fragment of the emotional control system is shown in **Fig. 1**. The unit *Actions* contains a set of behavior procedures. Each such procedure is activated by signals received from the unit *Need* and the signals from the special element *Gate*. Gate is the element that receives the direct signal from the sensors and the feedback signal from the output elements (in **Fig. 1** the internal sensor is indicated by yellow and external sensor is indicated by green color). Each output procedure has a specific emotional weight according to $E_i=N_i(a_i - a_i^{actual})$ (4). This signal is the input for the gate element. Therefore, the positive emotions associated with the action a_i will increase the activity of this action. Each action corresponds to a fixed action patterns (FAPs) [1] which is implemented using one or more Mealy machines. Service neurons stabilize the output vector. At each time, the robot performs only one action. The signal from the output of each service neuron arrives at the input to the inhibition of all other service neurons, suppressing their activity.

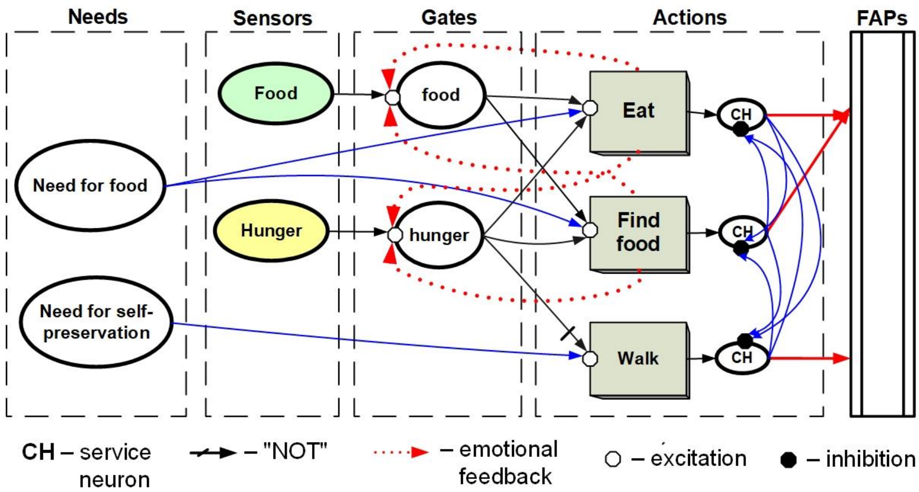

Fig. 1. Fragment of the emotional control system

The need-emotional control system makes it possible not to introduce artificial rules for the functioning of the animat but to determine its activity in terms of needs and the possibilities for their satisfaction.

The Organization of Interaction. For the organization of joint action, animat must be able to recognize each other and distinguish between their own groups and others. Let each animat correspond to some number—its identifier (Id). This number is generated automatically at the beginning of work. The values of identifiers are divided into ranges—one per group; the belonging of the Id value to the range determines the belonging of the animat to the group (i.e., it imitates the smell tag of the nest). When meeting each other, animats generate a signal whose value is equal to the Id. By accepting this signal, they can understand who is in front of them: their own type or a different one. Moreover, the value of the Id can be interpreted as the rank of the animat, which depends on its internal state. Based on this rank, it is possible to determine the domination relationship between individuals.

The Mechanism of Foraging. Karpova [15, 16] proposed a method for solving the problem of searching resources (first of all, food) simulating the foraging mechanism of ants of the genus Formica rufa. Foraging consists of three stages:

1. The search for food in the feeding region.
2. The return home.
3. The repetition of the way to food and back.

Ants of the genus Formica rufa do not use pheromones, unlike many other ants species, when inspect the foraging area and returning home [12, 17]. They can be guided by a single light source (the Sun or the Moon), by the direction of light oscillations (the sky polarization in natural conditions) and by visible landmarks. In areas close to the nest, they use mostly visual reference points.

In [16], rules were developed for memorizing a route consisting of visual landmarks. The route contains landmarks in the sequence in which the animat saw them while moving in the process of searching for food. The route description included a list of visual landmarks and their position relative to the animat (left / right or forward in the direction of motion). In order for the animat to return home and repeat this route, rules have been created that interpret the route description. Difficult behavior "Pass a known route" was divided into relatively simple actions, such as "Bypass landmark X on the right / left," "Move to landmark X," and so on. The action is an elementary behavioral procedure; each behavioral procedure is implemented using Mealy machine.

Ants use various methods for mobilizing foragers. Ants of the genus Formica, for example, have two options [17]: 1) a scout transmits route information to foragers, and those independently go for food; 2) a scout leads foragers behind him. In Karpova's previous works the first option was considered, and now it is necessary to implement the second option. The process of mobilizing foragers (followers) must be initiated by some kind of a signal. The role of such a signal in ants is played by food exchanges (trophallaxis) and special poses that the scout takes.

Moskovsky, Burgov, and Ovsyannikova [18] describe the system of visual analyzer of an animat, which has the basic possibility of recognizing an animat's pose. But due to technical difficulties with the imitation and the recognition of the postures of a robotic device, we will initiate mobilization using signals. For example, Karpov and Karpova [19] describe the task of pack hunting. The leader of the pack generates some signal during the execution of a fixed behavioral procedure. In other words, the robot notifies its surroundings about its action or state. Other members of the group perceive the leader's signal as a call and follow him. This could be implemented on the basis of imitative behavior, as described by Karpov [20], but this is beyond the scope of this work. We assume that the signal starts an appropriate behavioral procedure, which is part of the eating behavior.

The Aggressive Behavior Model. Aggression is an integral part of many types of animal behavior: parental, territorial, group (hierarchical), and so on. Karpova and Karpov [21] considered a model of aggressive behavior that takes into account the experience of previous clashes (participation in conflicts) and simulates the phenomenon of increasing aggressiveness with the age of the animat and the effect of forgetting one's own experience. In addition, Karpova considered a model of territorial behavior based on aggression toward aliens [22]. These models are responsible for the realization of the domination relationship and the imitation of the struggle between individuals.

The model of aggressiveness proposed by Karpova and Karpov [21] includes two parameters and the internal sensor "aggressiveness," the value of which affects the animat behavior. The parameter A_0 sets the initial aggressiveness level, and the parameter A_C sets/measures/represents the current level. A_C determines the current tendency of the animat to enter into conflict. The A_C is increased by a certain amount δ in each time step, which imitates the increase in ant aggressiveness with age [7]. In addition, the value of A_C increases after the animat wins (W = 1) and decreases after its defeat (W = 0). The level A_C increases in case of victory at the moment of time *t* and is determined as monotonically increasing function with rage of values [0, 1), for example:

$$A_C(t) = 1 - e^{-\alpha t}, \quad (5)$$

where α is amplification factor of a synaptic connection.

In case of defeat the level decreases, and its value is defined as monotonically decreasing function with rage of values (0, 1], for example:

$$A_C(t) = e^{-\beta t}, \quad (6)$$

where β is attenuation factor of the synaptic connection.

In finite difference equations, the change in A_C can be expressed as follows:

$$\Delta A_C = \alpha(1 - A_C(t)), \text{ if } W=1 \quad (7)$$

$$\Delta A_C = -\beta A_C(t), \text{ if } W=0 \quad (8)$$

In fact, aggressiveness describes a measure of animat activity / passivity. This is a conditional indicator, which is convenient to use to describe the behavior of the animat. If desired, aggressiveness can be replaced by any other indicator, signal, or action. For us the main thing is to understand whether the animat is ready to obey. In ants, it depends primarily on the aggressiveness level. Therefore, we will not introduce any special parameters or signals but use precisely the aggressiveness level that has already been implemented in the animat's control system by Karpova and Karpov [21] ("Sensor A" in **Fig. 2**).

3.2 New Mechanisms and Methods

The control system has been supplemented by the “Recruitment signal” sensor and “Need for cohesion” [11] (see **Fig. 2**). This need coordinates the group behavior of the individuals during the raid. Also, a fixed action pattern “Follow the Leader” was implemented.

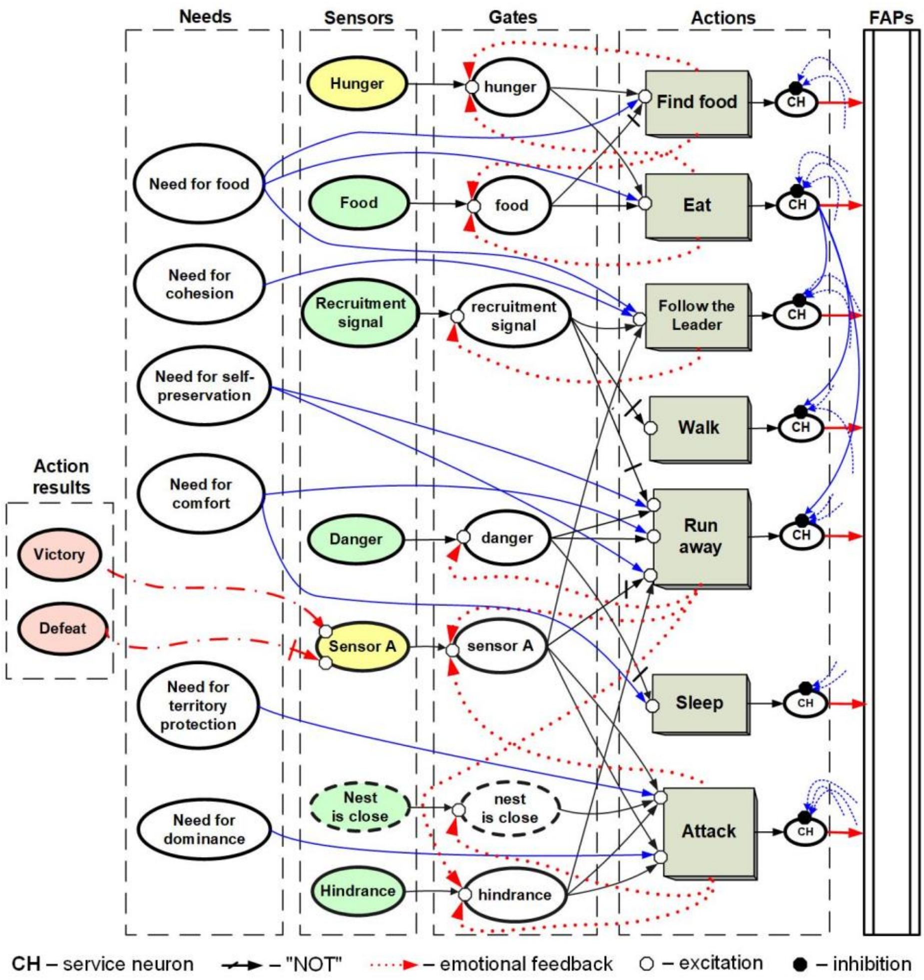

Fig. 2. The architecture of the emotional control system with an aggressive component

The Submission Mechanism. A mechanism of subordination is required to realize the phenomenon of slavery. Both food and a passive ant of another species are resources for active foragers. But a forager cannot change another individual and transfer it from an active to a passive state. The transition to a passive state must occur at the initiative of the one who obeys. Therefore, a weak ant takes the posture of submission when meeting an aggressor. For an animat, this means a change in the internal state, which leads to a decrease in its rank. Let the Id of the animat be interpreted as rank and depend on the level of aggressiveness. Then, we do not need additional alarms or artificial methods to simulate a duel, as shown by Karpova [22]. Changing the rank leads to the generation of the corresponding signal. This signal turns a weak animat into a resource attractive to foragers. And the forager transports this “resource” to its nest.

Adaptation in Another Nest. The socialization of an individual in another nest is achieved by acquiring the nesting odor and reducing the aggressiveness level of the individual. We need to imitate this and, if possible, in a simple way. Suppose that after hitting a foreign nest, the animat changes the value of its Id to the minimum value from the range of this nest. Thus, he not only becomes acceptable for the inhabitants of this nest but also receives the minimum rank. This corresponds to the level of its “success.” In the future, its rank will increase in accordance with an increase in the aggressiveness of ants with age.

4 Simulation Experiments

To confirm the efficiency of the proposed method, simulation was performed using the multi-agent modeling system Kvorum [23]. Let there be a field in which there are some agents of two groups A and B. The field has a limited size and forms a toroidal surface, that is, the edges of the field are closed (see **Fig. 3**). Our intention is to consider the task of organizing raids and foraging (in **Fig. 3** food is indicated by a small blue square). Each group of animats has its own “nest” (in **Fig. 3** the nest is indicated by a big square). A series of experiments was carried out with the redistribution of animats between groups. The total time of one experiment was 3000 cycles, N = 10; 20.

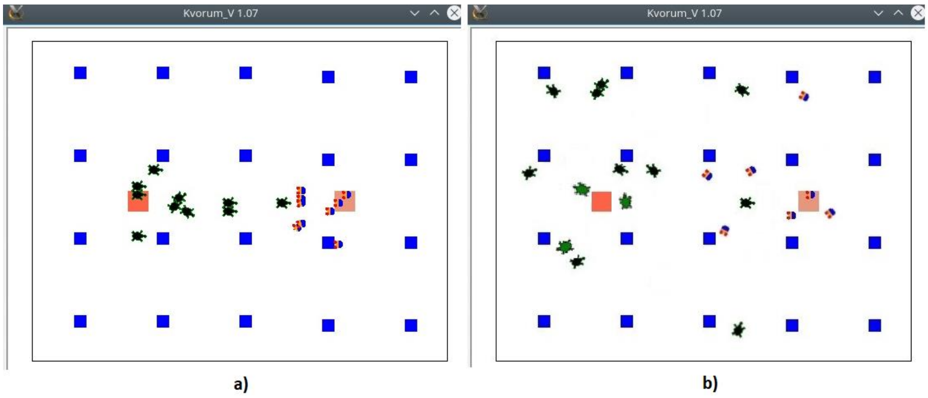

Fig. 3. Examples of experiments: a) organization of the raid;
b) foraging after the animats redistribution (green animats moved to another group)

To speed up the simulation, the experiments were carried out according to a simplified scheme:

1. The reconnaissance of the first group leads animats to the second nest.
2. Fights take place at the second nest.
3. The subordinate individuals of the second group are delivered to the first nest.
4. Both groups are engaged in foraging.

The stages of searching for food (resource) and returning to the nest have been described and implemented in [16]. For a raid, passive foragers are always recruited inside or near the nest [24], so this simplification does not contradict the observations of ants.

The animats had the following features. They could move back and forth, turn left and right. They have two internal sensors: the hunger sensor and the aggressive sensor. Also the animats were equipped with four IR sensors. Each sensor "hears" a signal from a certain side (in front, behind, to the left and to the right). The hearing area of the animat is limited. The animat generates a broadcast signal that can only be received by its close neighbors.

There is no sense in presenting any statistical data obtained in the course of the experiments and giving estimates. We can set different values of the model parameters and get any data: from the minimal susceptibility of animats to "enslavement" to the complete transition of all animats to one group. But these experiments faced another challenge. They were designed to confirm the applicability of the proposed approach and the efficiency of the developed models and algorithms. This goal was achieved.

5 Conclusion

The proposed approach allows us to solve the problem of redistributing animats between groups under the following conditions. The problem is solved in the conditions of local communication and without centralized control. Animats have a set of needs (dominance, self-preservation, food and so on), a set of procedures that implement some types of behavior (food, aggressive, contagious), and a set of rules that ensure the transition from one procedure to another. Each of them independently makes decisions about its actions, but together they form a society and act for the benefit of this society.

Of course, to solve the problem of redistributing animats between groups, a different, simpler method could be used. It is even possible that this other method would show better controllability and higher efficiency. But, first of all, the current work is designed to demonstrate that complex behavior can be implemented using previously created models, methods, and mechanisms in the framework of social behavior modeling. And secondly, the proposed method can be used to form heterogeneous robots groups in the future.

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