Biologically Inspired Model of Adaptive Searching Behavior*

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Abstract – The computer model of searching adaptive behavior is constructed and investigated. The model describes searching behavior of caddis fly larvae which inhabit creek bottoms and build their cases using hard particles of different size. Using large particles, the larva can build cases more quickly and effectively than with small particles, so it prefers large ones. Inertial switching between search tactics takes place. The model is compared with results of biological experiment. The results of simulation are adequate to biological data.

Keywords: Adaptive behavior, modeling, searching for adequate tactics

1. INTRODUCTION

The direction of research "Adaptive behavior" appeared in the beginning of 1990th [1,2]. The basic approach of this direction is a designing and investigation of artificial "organisms" (in the form of computer programs or robots), capable to adapt to an environment. Those organisms were called "animats" (from animat = animal + robot). The minimalist program of this direction is to investigate architecture and principles of functioning which allow animals or robots to live and operate in variable and poorly predictable environments. The maximalist program is to analyze evolution of animal cognitive abilities and an evolutionary origin of human intelligence [3]. By modeling an adaptive behavior of animats researchers try to use designs which, in their opinion, can be present in alive organisms.

One of the main tasks of investigation is to study searching behavior of animals [4]. The searching behavior of caddis fly larvae which are searching for hard particles of appropriate size to build their cases is investigated in this paper. The computer model of adaptive searching

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behavior of caddis fly larvae is constructed and investigated. It is demonstrated that the model is adequate to biological data.

Section 2 outlines the biological experiment on caddis fly larvae. The computer model and simulation results are described in Sections 3, 4. Section 5 includes the discussion of the results.

2. BIOLOGICAL EXPERIMENT ON CADDIS FLY LARVAE

The caddis fly larvae inhabit creek bottoms and build their cases from hard particles of different size [5]. They can use small or large sand particles. Large particles are distributed randomly over a bottom, but typically occur in groups of several particles. Using large particles, a larva can build cases more quickly and effectively than with small particles, so larvae prefer large particles. The larva uses two tactics: 1) testing particles in its vicinity and building the case from selected particles; testing consists of touching and rotating a particle with legs, 2) searching for a new place with a collection of appropriate particles. If the larva finds a large particle, it continues testing other particles in the same spot until it finds several small particles, and only after repeated failures to find new large particles does the larva switch to the second tactic; this switching is inertial. During the search for a new place, the larva wanders and sometimes randomly tests particles along its way. It can switch from the second tactic to the first one if it finds a large particle. When switching from the second tactic to the first tactic, it may also exhibit inertia, namely, a large particle may be dropped and the larva proceeds moving. Thus, the switching between tactics resembles a random search with inertial effects. As a result of the inertial switching, the larva behavior reflects only general large-scale patterns in the environment.

Simple computer model of larvae behavior was built [5]. The model assumes that the degree of readiness R to an attachment of the next particle i depends on the readiness corresponded to the previous particle (i-1), and on relative difference in sizes q of these particles:

$$R_i = aR_{i-1} \exp\,[b(q_i - q_{i-1})\,/q_{i-1}], \tag{1}$$

where a and b are positive parameters. The larva attaches the particle i if readiness R exceeds the certain threshold that is equal to the size of the last attached particle (even if the attachment took place long before the detection of the particle i). Otherwise the larva drops it and start testing other particles. If readiness falls below some threshold, the larva stops particle testing and starts to move, and the lower is the readiness, the longer is the movement duration. At an appropriate choice of parameters, this model quantitatively reproduces a choice of actions, including a primary (but not exclusive) choice of large particles, preference of sites with large particles and changes of particles testing duration.

However this model [5] describes only actions of larvae, but does not describe temporal dynamics of behavior. The current paper describes the model that reproduces time dynamics and can be compared with the theories of function optimization.

We are designing the computer model basing on concrete biological experimental data. The following biological experiment has been put in [6]. Caddis fly larvae (Chaetopteryx villosa) were placed in a ring corridor filled with water, which bottom has been covered by a continuous layer of sand. The most part of the bottom (the region 1) was covered with sand grains (small particles) only. In the smaller part (the region 2), large flat particles (square-shaped fragments of egg shells), preferred by larvae, were mixed with sand. Diameter of the ring was 87 mm, width of the ring was 16 mm. The area of the region 2 was equal to 1/6 of the ring area. The linear size of small particles was 0.5-1 mm, the size of large particles (egg shell fragments) was 1.5-2 mm. The characteristic size of a larva was 12 mm. Probability of that the larva meets a large, instead of a small particle in the region 2, was approximately 0.2.

The behavior of 40 larvae was observed in the experiment [6]. The foremost and hindmost parts of already constructed larva cases have preliminary been destroyed. The larva was initially placed in the center of the region 1. The larva behavior observed for 1 hour after an attachment of the first particle. Occasionally a larva did not attach any particle for too long time (the order of 1 hour). Experiments with such larvae were not used for data analysis.

The behavior of larvae was as follows. Before to begin a case construction, larvae moved along the corridor and tested significant number of particles. All individuals visited the region 2 during this movement and tested both sands and shells. Four larvae began construction within the region 1 and did not come back to the region 2 until the end of the experiment. All other individuals began construction with an attachment of a shell within the region 2, and 17 of them did not leave any more this region. The remained 19 individuals spent more than a half of observation time within this region. Larvae, which remained within the region 1, have attached 7 sand grains on the average. The average number of the attached particles for 17 individuals, who remained on the region 2, and for 19 individuals, who repeatedly left and returned back the region 2, was 5 shells and 2 grains. The experiment shows that caddis fly larvae prefer the region 2, where they build cases mainly of large particles.

3. COMPUTER MODEL

We design a model of search behavior of caddis fly larvae under the following assumptions.

1) The time is discrete. The time step Δt is equal to the minimal characteristic time in larvae behavior, namely it is of the order of 1 second.

2) The movement of larvae along the ring is one-dimensional, that is we neglect width of a ring in comparison with its diameter d.

3) The larva has two tactics of behavior: A) to search particles in its local vicinity and attach particles to the case, and B) to move on a new place.

4) At tactic A) two operations are possible: testing of a particle and the attachment of a particle to the case.

5) There is a motivation to the attachment $M(t)$. Dynamics of $M(t)$ is determined by the expression:

$$M(t) = k_1 M(t\text{-}\Delta t) + \xi(t) + I(t) , \qquad (2)$$

where k_1 is the parameter describing a slow decrease of the motivation ($0 < k_1 < 1$, $1\text{-} k_1 \ll 1$); $\xi(t)$ is normally distributed random variable, the average and the standard deviation of $\xi(t)$ are equal to 0 and σ, respectively; $I(t)$ is the stimulus intensity. At testing, the stimulus intensity is determined by the expression:

$$I(t) = k_2 (S_{curr} - S_{last})/ S_{last} , \qquad (3)$$

k_2 is the positive parameter; S_{curr} the area of larva's body covered by the presently tested particle, S_{last} is the area covered by the last tested particle (for the sake of brevity, these areas will be referred to as "area of particle(s)"). At an attachment and moving, the stimulus intensity is equal to 0: $I(t) = 0$.

6) Testing and attachment occur if the motivation $M(t)$ exceeds the certain threshold. The thresholds for testing and attachment are different. The threshold for testing H_{test} is proportional to the area of the last tested particle S_{last}: $H_{test} = k_3 S_{last}.$ The threshold for attachment H_{att} is proportional to the area of the last attached particle S_{att} : $H_{att} = k_4 S_{att}$. k_3 , k_4 are positive parameters.

7) The scheme of action performance is as follows. If the motivation $M(t)$ exceeds the testing threshold H_{test} and there is no attachment then larva starts to test the nearest particle. If the

motivation $M(t)$ became less than the threshold H_{test} at testing, then the tested particle is rejected. If the particle is not rejected at the testing procedure, testing proceeds during certain time $T_{test,}$, and then the motivation $M(t)$ is compared with the attachment threshold. If $M(t) < H_{att,}$, the particle is not attached; if $M(t) > H_{att}$, the particle is attached during time T_{att} (at the attachment the motivation $M(t)$ is not compared with the threshold H_{att}). Durations of testing T_{test} and attachment T_{att} depend on the particle size. If the larva does not test and does not attach a particle, it moves.

8) When the movement begins, the larva chooses a direction of the movement at random (with the probability 0.5 for each of two possible directions) and moves for a while in this direction. Incidentally, with an interval in T_{change} , the larva chooses at random a new direction of the movement along the ring.

9) Length of one movement step (during the time Δt) equals to L.

It should be noted that in accordance with [5], a larva remembers the sizes of last tested and attached particles and uses the memory about these particles at the organization of its behavior.

3. RESULTS OF COMPUTER SIMULATION

At modeling, as in the biological experiment [6], it is supposed, that larvae are placed in the ring corridor, diameter of the corridor d is equal to 90 mm. The sector of 1/6 part of perimeter (the region 2) contains particles of two sizes: small (grains) and large (shells), the other part of the corridor (the region 1) contains only grains. The linear sizes of small and large particles are 0.5 mm and 1.5 mm, respectively. The area of any particle is equal to the square of its size. Probability that a larva meets a large particle within the region 2 is equal to 0.2. The time step Δt is equal to 1 second. Initially a larva is placed in the center of the region 1. The initial motivation to the attachment is equal to zero: $M(0) = 0$. The initial attachment threshold is equal to $H_{att}(0) = k_4 S_L$, where S_L is the area of a large particle. Then this threshold exponentially decreases with characteristic time that is equal to 3000 time steps, until the first particle is attached; then the threshold $H_{att}(t)$ is determined by the sizes of attached particles.

The initial testing threshold is equal to $H_{test}(0) = k_3 S_S$, where S_S is the area of a small particle; the threshold H_{test} is not varied until testing begins. According to experimental data, the length of one movement step is equal to L = 2 mm. The testing time T_{test} of a small and large particle is 5 seconds and 10 seconds, respectively. The attachment time T_{att} of a small and large particle is 60 seconds and 120 seconds, respectively. The time of movement direction change T_{change} is 30 seconds. Other parameters of the model (k_1- k_4, and σ) have been chosen as follows.

As characteristic time of an attachment is of the order of 100 seconds, the characteristic time of relaxation of the motivation should be of the same order: $k_1 = 0.99$. Parameters k_3, k_4 have been chosen as follows: $k_3 = 0.01$, $k_4 = 1$. Parameters k_2 and σ were roughly varied within the range 0.001 to 0.1 and have been chosen to obtain the behavior, that is similar to real biological data, namely $k_2 = 0.007$, and $\sigma = 0.05$. The computer simulations were performed during 7200 time steps; this corresponds to 2 hours for modeled processes.

Analogously to the biological experiment, the behavior of 40 larvae within 1 hour after the attachment of the first particle was analyzed. If no particle is attached within 1 hour after the beginning of calculation (there were 3 such calculations among 43 simulations) analogously to biological experiment such calculations were not taken into consideration.

The behavior of modeled larvae had following properties:

- At the beginning of calculation larvae moved along the ring corridor, in most cases (in 27 calculations of 40) visiting and leaving the region 2 till the moment of an attachment of the first particle. In 13 calculations larvae began process of an attachment within the region 2 during the first visit to this region.
- The average time from the beginning of calculation till the moment of an attachment of the first particle was 1815 seconds (the standard deviation of this time was 872 seconds).
- In almost all calculations (in 39 calculations from 40) a large particle was attached first.
- The average number of attached particles during one hour was 4.2 large particles (the standard deviation was 1.68) and 0.6 small particles (the standard deviation was 1.53).
- In 14 calculations the larva did not leave the region 2 after the beginning of the particle attachment, in 10 calculations the larva was outside of the region 2 at the end of observation. In 16 calculations the larva left from the region 2 and return back to this region.

Quantitative characteristics of larvae behavior are presented on Figs. 1-3.

The time dependences of change of the total area of a larva case $S(t)$ for three typical calculations are shown on Fig. 1. The figure demonstrates that 1) numbers of attached particles are small and close to the average number observed in biological experiment, 2) there is a strong dispersal in the number of attached particles and in the time of beginning of the attachment of the first particle, 3) large particles (that have the area 2.25 mm^2) are mainly attached, but small particles (that have the area 0.25 mm^2) are incidentally also attached. Let's note that the dependence 1 on Fig. 1 corresponds to the maximal number of the attached small particles. The attachment of small particles was observed only in 8 calculations of total 40 (in 3 calculations one small particle has been attached, and in 5 other calculations 2,3,4,5 or 7 small particles have been attached, one calculation for each of these numbers).

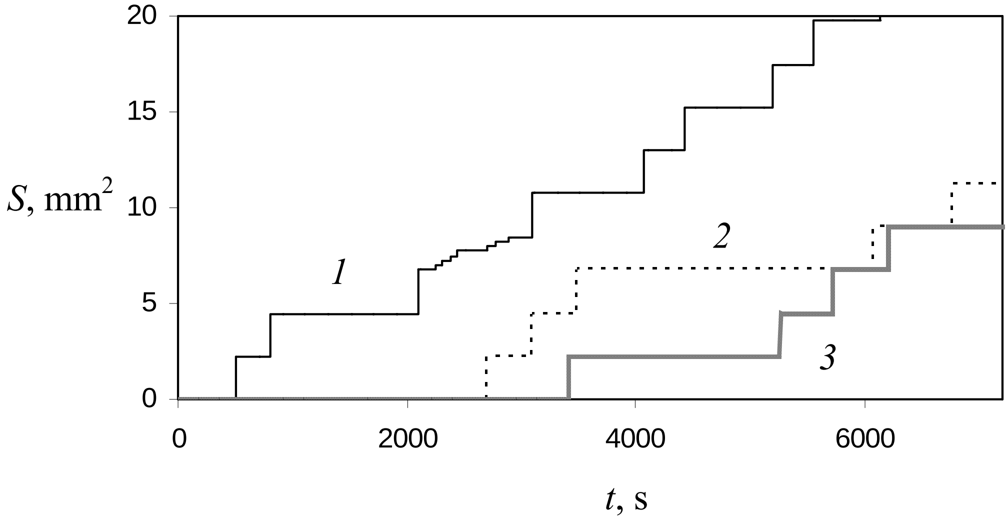

Fig. 1. Time dependence of the total area of attached particles $S(t)$ for three various calculations. At sharp jumps of $S(t)$ large particles are attached, at small jumps of $S(t)$ small particles are attached. The large variability of the time of the attachment beginning and the number of attached particles is visible.

The details of the individual larva behavior (example *3* in Fig. 1) are illustrated by Figs. 2, 3. Fig. 2 shows the time dependences of the total area of attached particles $S(t)$ and the normalized angular coordinate $\phi_{norm}(t)$ of the larva. The time dependence of the motivation to attachment $M(t)$ is presented on Fig. 3. The dependences are shown from the moment $t = 3000$ to the end of calculation. The normalized angular coordinate $\phi_{norm}(t)$ corresponds to the interval $[0, 2\pi]$; the center of the region 1, in which a larva is placed when the calculation is beginning, corresponds to $\phi_{norm}(t) = 0$, the region 2 corresponds to the interval $(5/6)\pi < \phi_{norm}(t) < (7/6)\pi$.

Let's consider details of the larva behavior (Figs. 2, 3). After $t = 3018$ the larva is within the region 2, its angular coordinate does not vary until $t = 3430$. During the initial moments within the region 2, the motivation $M(t)$ is below the attachment threshold (Fig. 3), therefore attachments of particles do not occur, and only a testing and rejection of particles (large and small) is observed. As the larva tests large particles within this region, there is the motivation increase $M(t)$ according to expressions (2), (3) during testing of large particles after small particles. This growth of the motivation $M(t)$, accompanied by decreases of $M(t)$ at testing of small particles after testing of large particles and relaxation of the motivation, takes place till the moment of time $t = 3288$, when the motivation $M(t)$ exceeds the attachment threshold H_{att} and the attachment of the large particle begins. The attachment proceeds till the moment $t = 3408$, the essential decrease of the motivation (down to the value 0.4) occurs during this period. Then testing of particles is accompanied by fluctuations of the motivation, and after the moment t = 3430 the motivation falls below the testing threshold, and the larva begins to move.

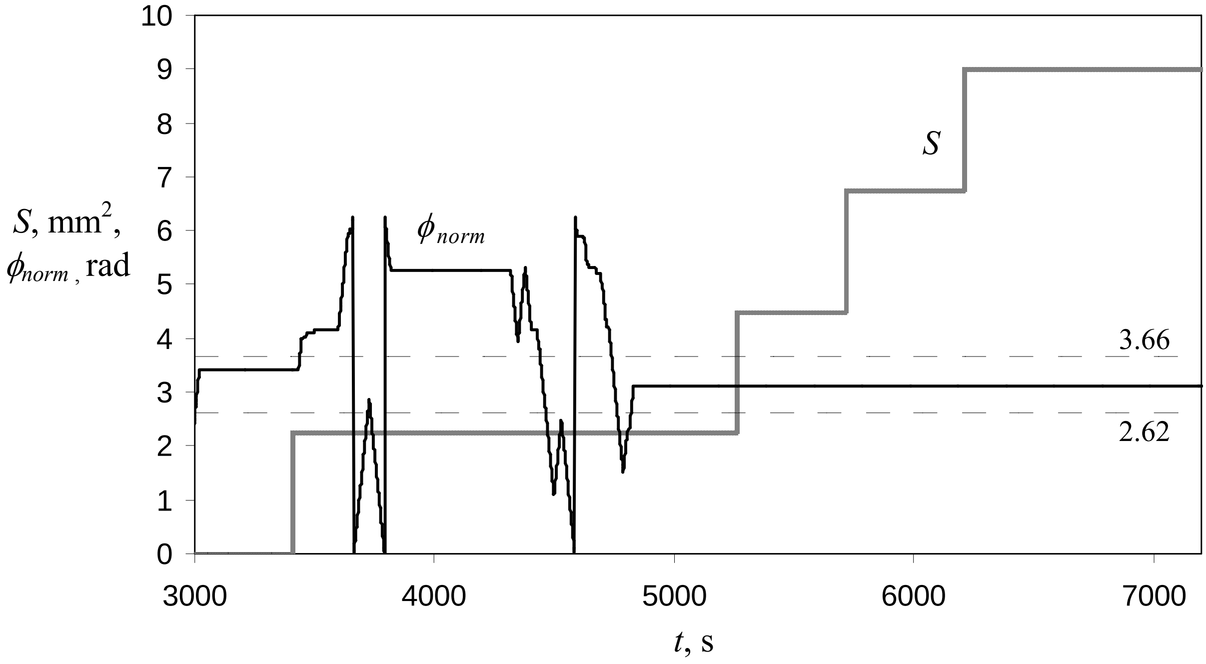

Fig. 2. Time dependences of the total area of attached particles $S(t)$ and the normalized angular coordinate $\phi_{norm}(t)$ for the calculation corresponding to the example *3* (Fig. 1). t > 3000. The angular coordinate $\phi_{norm}(t)$ is normalized to the interval [0, 2π]. Horizontal dashed lines correspond to boundary values $\phi_{norm}(t)$ of the region 2.

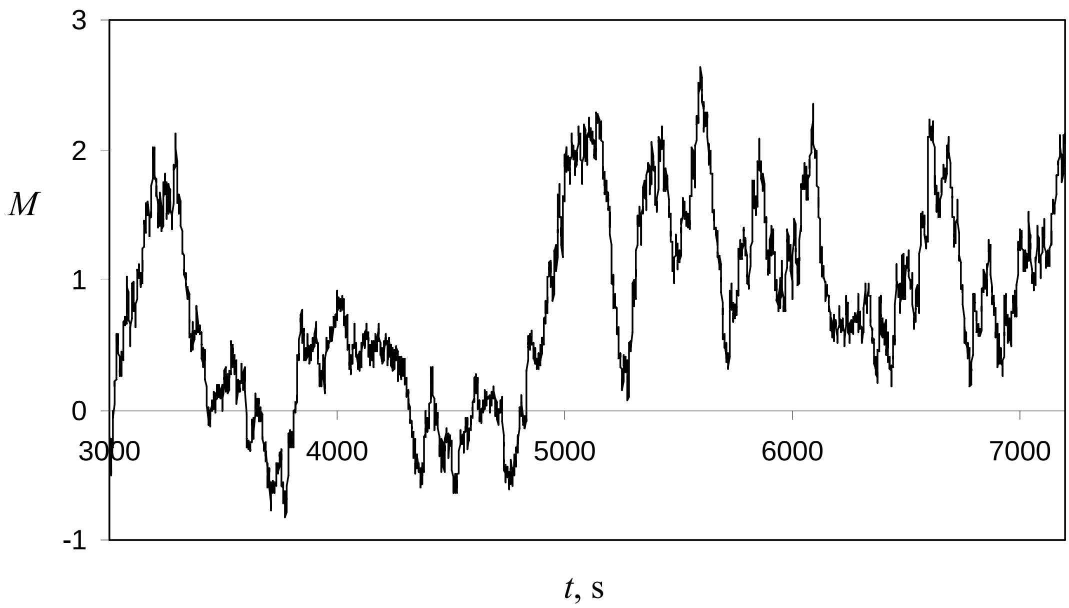

Fig. 3. Time dependences of the motivation $M(t)$ for the calculation corresponding to the example *3* (Fig. 1). t > 3000.

Then the movement is sometimes interrupted by testing and rejection of particles, until t = 4830, when the larva again gets to the region 2. At testing large particles there is the growth of the motivation $M(t)$; as a result, the new large particle starts to be attached at t = 5140. Then there is the decrease of the motivation again, but this decrease appears not so significant as after the attachment of the first particle, and the larva remains within the region 2 and the process of the testing and the attachment of particles takes place until the end of calculation.

As it was noted above, the model supposes that larvae have the memory about the sizes of last tested and attached particles and use this memory at the organization of adaptive behavior. We attempted to construct other model without such memory in which there is an optimization of average growth rate of the area of the larvae case (analogously to [7]). However, simulations demonstrated that such model does not correspond to biological data, namely, there is no preference of attaching large particles. So the memory about the sizes of last tested and attached particles is important.

4. DISCUSSION AND CONCLUSION

Thus, the computer model of searching behavior in larvae, which build their cases of large and small particles has been constructed and investigated. The model shows the behavior similar to that of real larvae. It is demonstrated that the memory about the sizes of last tested and attached particles is necessary to for biologically adequate modeling.

The interesting mechanism of the motivation regulation is included in the current model; this mechanism corresponds to the principle of partial success: at testing a large particle, which is not attached because of a small level of the current motivation, there is the growth of the motivation $M(t)$, therefore the tendency for the attachment of a next large particle is increased. Note that the principle of partial success is known for other animals [8,9].

The designed model is characterized also by inertial switching between behavioral tactics, this can be used for a development of artificial autonomous adaptive systems with several need and goals. Note that both the principle of partial success and the inertial switching emerge from the same property of our model, described by the term $k_1M(t\text{-}\Delta t)$ of the equation (2). Thus, the equation (2) provides a simple way to model these biologically plausible and adaptive behavioral traits.

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