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Adaptive Behavior to Environmental Changes: Emergence of Multi-generational Migration by Artificial Monarch Butterfly

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Abstract: The target of our study is the Monarch Butterfly, which is known for its multi-generational migration behavior: it migrates between southern Canada and Mexico over the course of one year within three to four generations. We approach this subject by using an evolutionary simulation that is an ecosystem consisting of artificial agents and five areas. We focus on the metamorphosis and the reproductive diapause, which are the ecological characteristics of the Monarch, and we design a model of agent which has the state as its inner parameter. We simulate under the environmental condition that the average annual temperature rises every year, which is modeled on the current global temperature rise. Our agents emerge the migration behavior similar to the multi-generational migration behavior of the actual Monarch. The migration process of the agents and their genetic factors are discussed, and our proposed model and the previous model are compared.

Keywords: Artificial Life, Adaptive Behavior, Monarch Butterfly, Evolutionary Simulation

1 INTRODUCTION

One academically valued of studying the behaviors of these organisms is evolutionary simulation based on models. Computer-simulated virtual ecosystems allow us to perform experiments rapidly and repeatedly, and the evolutionary processes of artificial organisms can be observed. Even if an agent has only a simple mechanism, if key aspects of behaviors are modeled, complex behaviors can be obtained through the evolutionary process [1].

The subject in our study is the Monarch Butterfly (*Danaus plexippus L., Nymphalidae, Lepidoptera*). This butterfly is known for its multi-generational migration behavior: it migrates between southern Canada and Mexico over the course of one year within three to four generations. Their life cycle has been detailed in reference [2] and our previous paper [3]. In spite of many reported studies [4], [5], [6], little is known about what influences their migration.

We have designed a model for the migration behavior of Monarchs by adaptiogenesis to environments with sensory agents in the previous research, but the previous model was incomplete because of many differences between the migration behavior emerged by agents and actual migration of Monarchs. In this paper, we focus on the metamorphosis and the reproductive diapause, which are the ecological characteristics of the Monarch, and we design a model of agent which has the state as its inner parameter. The agent changes its state depending on inner or outer information, and this changed state causes characteristic alterations. Additionally, we included the day length in the area models as an environmental factor because entomology shows that agent transformation depends on both temperature and day length. We show the advantage of our model by comparing the result with actual migration behavior of Monarchs and the previous model.

1.1 Area

The ecosystem has five areas that we label as $area_0$, $area_1$, ... , $area_4$ from south to north. Each area is modeled after the area of North and Central America (Table 1) where the migration of Monarchs actually occurs and consists of a two-dimensional 40×40 grid. $area_i$ has three environmental parameters, which are temperature, day length, and foods. These three environmental factors have significant effects on the migration of the Monarch. Each parameter is explained below.

Table 1. Five areas.

$area_i$	Model city
$area_4$	Minneapolis, U.S.A.
$area_3$	Kansas City, U.S.A.
$area_2$	Oklahoma City, U.S.A.
$area_1$	Austin, U.S.A.
$area_0$	Michoacan, Mexico

1.1.1 Temperature.

Temperature is decided by two kinds of environmental changes: long-term and short-term. A long-term change is an annual temperature rise and a short-term change is a daily change of temperature. To configure short-term change, we used real data from the past 20 years in each original area (collected by the National Climate Data Center [7]) and calculated the average annual data by trigonometric function. Thus, we define a temperature $tmpr_i(y,d)$ in $area_i$ at year y and day d as

$$tmpr_i(y,d) = short_i(d) + 0.01 \times y, \tag{1}$$

where $short_i(d)$ is short-term change in $area_i$. In this paper, the average annual temperatures of all areas rise $0.01°$ F every year.

1.1.2 Day Length.

In this paper, we newly focused on the day length as one of the environmental factors. The day length is defined as the time difference from sunrise to sunset. We can compute the time of sunrise and sunset using latitude, longitude, and altitude by the computation approach in reference [8]. We use real data to compute day length of each area.

1.1.3 Food

Each area has foods used as source of vital energy for the agents. The number of foods N_i in $area_i$ is determined by

$$N_i(t) = N_i(t-1) + \mathrm{M_F} \times incFood(\mathrm{S_F}, tmpr_i(t)), \tag{2}$$

where t is the number of steps ($t = \mathrm{DAY} \times y + d$, where DAY is a certain fixed number of days in one year), $\mathrm{M_F}$ is the maximum increment of foods in one day, and $\mathrm{S_F}$ is the most suitable temperature for increment of foods. $incFood()$ is the function which determines the increment of foods and outputs a real number while 0 to 1. The output of $incFood()$ is inversely proportional to the difference between $\mathrm{S_F}$ and $tmpr_i$. The life-span of the plant is $\mathrm{L_F}$. A food is removed from the simulation when it is eaten by the agent or reaches the end of its life-span.

1.2 Agent

An agent can sense internal information, and external information. By using sensory information, an agent decide its action and decide its state only once a day. In this paper, the behavioral strategy and the transformational strategy are expressed by n-output binary decision diagram (n-BDD) [9], which is an extension of BDD [10]. An agent $agent_j$ (j is identifier) has four genetic component and characterized as

$$agant_j(ea_j, cs_j, ast_j, sst_j), \tag{3}$$

where ea_j is a thermal sensitivity, cs_j is a cold resistance of the diapause agent, ast_j is the behavioral strategy, and sst_j is the transformational strategy. We describe ea_j and cs_j in Section 1.2.3, ast_j in Section 1.2.4, and sst_j in Section 1.2.5.

1.2.1 Action.

Five actions — W, E, R, Mn, and Ms — can be performed by the agent. An agent that selects W stays in the same grid of the same area for one day. An agent that selects E increase its energy by eating a food. If there is no food in its visual field, the agent moves at random looking for foods. An agent that selects R reproduces a new agent with another agent. If there is no agent in its visual field, the agent moves at random looking for agents. The Mn and Ms are the migration behavior. An agent that selects Mn migrates from $area_i$ to $area_{i+1}$ and that selects Ms migrates from $area_i$ to $area_{i-1}$ in 10 days. If there is no destination area, the agent changes their action to W.

1.2.2 State.

We newly focused on the "states" of the agents, which we neglected in the previous study. An agent has the state $state_j$ as its internal parameter. We defined three states — Cp, Dp, and Rp — which an agent can enter. The state determines which action an agent can select, if and when it can transition the state, and how long it can stay in the state.

The Cp state is the stage of an egg, a larva, or a pupa. An agent is in the Cp state, which is an initial state when it is first born. In the Cp state, only W and E are selectable actions and the agent can transition its state to either Dp or Rp. The Dp state is the reproductive diapause stage of an adult. An agent in the Dp state can select any action except R and can transition to Rp when the transition condition is met. The Rp state is an adult stage that can reproduce. All five actions are selectable in this state and can never transition back to the other two states. The age age_j, which is the maximum life-span of the agent in the state $state_j$, is initialized by L_{state_j} when the agent changes its states.

1.2.3 Sense.

All agents can sense the seven pieces of information. X_m has a truth-value, true or false. X_0 is information about whether the agent is in the diapause. X_1 is about whether the energy level is in the condition of "$in_j > \mathrm{I_B}$", where in_j is the amount of energy which agent stores and $\mathrm{I_B}$ is a specific energy level. An agent has a visual field (8-point neighborhood) and can sense the other agent and the food in its visual field. X_2 is information about whether other agents are in the visual field, and X_3 is information about whether foods are in the visual field. X_4 is information about the day length of the area; an agent can ask, "Are there more than 12 hours in this day?" X_5 and X_6 are information about the temperature of the area. To sense a temperature, each agent has up_lim_i and lo_lim_i, which are given by

$$lo\_lim_j = s_j - ea_j, \tag{4}$$

$$up\_lim_j = s_j + ea_j. \tag{5}$$

ea_j is an integer fulfilling $0 \leq ea_j \leq \mathrm{EA}$ (where EA is a constant) and represents the thermal sensitivity. An agent becomes sensitive to temperature changes when ea_j is small.

s_j is given by

$$s_j = \begin{cases} \mathrm{S_A}, & \text{if } state_j = \mathrm{Dp} \\ \mathrm{S_A} - cs_j, & \text{otherwise} \end{cases} \quad (6)$$

where $\mathrm{S_A}$ is the most suitable temperature of the agent and cs_j is an integer fulfilling $0 \leq cs_j \leq \mathrm{CS}$ (where CS is a constant). We observed that Monarchs in reproductive diapause pass the winter by reducing metabolic activity, so we set agents in the Dp state to be resistant to cold and agents in the Cp and Rp states to not be resistant. $X_5 = \mathrm{true}$ shows $tmpr_i < lo\_lim_j$, in which case the agent feels cold. $X_6 = \mathrm{true}$ shows $tmpr_i > up\_lim_j$, in which case the agent feels hot.

1.2.4 Action Decision Diagram.

The agent $agent_j$ decides which action $act_j(t)$ is performed every day by

$$act_j(t) = ast_j(X_0(t), \cdots, X_m(t)). \quad (7)$$

ast_j is expressed by 5-BDD with seven variables and five possible outputs: W, E, R, Mn and Ms.

1.2.5 State Decision Diagram.

The agent $agent_j$ decides to enter state $state_j$ by using counter $c_j(t)$, which is updated every day by

$$c_j(t) = c_j(t-1) + sst_j(X_0(t), \cdots, X_m(t)). \quad (8)$$

sst_j is expressed by 2-BDD with seven variables and two outputs: $+1$ or -1. The transition method of the two states is different. An agent, which reaches the end of its life in the Cp state ($age_j = 0 \wedge state_j = \mathrm{Cp}$), transitions a state. It can transition to Rp if $c_j(t) > 0$ or to Dp if $c_j(t) \leq 0$. In the Dp state, the agent can transition to Rp when $c_j(t) > 0$. In the Rp state, the agent cannot transition to another state.

1.2.6 Energy Level Update

After the action, the energy in_j is updated by

$$in_j(t) = in_j(t-1) + f(act_j(t), td), \quad (9)$$

$$td = |s_j - tmpr_i|, \quad (10)$$

where function f is the update function of the energy level. Increases or decreases to the energy level are directly determined by which action is selected and decreases are large if the value of td is also large. The E action is the only action by which an agent can increase its energy level and other actions decrease.

1.2.7 Reproduction.

An agent is generated from two agents by R action, which is the reproductive behavior. Four genetic parameters of a child agent are generated from that of both parents by crossover and mutation. We adopt two-point crossover for ea_j and cs_j, and uniform crossover for ast_j and sst_j. Let age_j, in_j, $state_j$, and c_j are each initialized by $\mathrm{L_{Cp}}$, $\mathrm{I_B}$, Cp, and 0, respectively.

1.2.8 Death.

If an agent suffers either one of the following conditions, it dies and is removed from the simulation.

$$in_j < 0 \quad \vee \quad age_j < 0, \quad (11)$$

Each condition means a starving and a natural death.

2 EXPERIMENTS AND DISCUSSION

In this section, we present the parameter settings and simulation results. We placed 200 agents with randomly generated genetic codes in $area_0$. Note that the experimental parameters in Table 2 are based on the actual biological features of the Monarch Butterfly and their habitat. We simulated 2000 years. All experimental results are the average of 30 trials.

Table 2. Parameters Setting.

DAY (1 year)	$\mathrm{S_F}$	$\mathrm{M_F}$	$\mathrm{L_F}$
365	65	30	30

$\mathrm{L_{Cp}}$	$\mathrm{L_{Dp}}$	$\mathrm{L_{Rp}}$
30	200	30

$\mathrm{S_A}$	EA	CS	$\mathrm{I_B}$
70	15	20	120

2.1 Experiment 1.

We simulated our proposed model. Fig. 1 shows the migration process from $area_0$ to the other areas that was obtained after 30 experimental runs. In the early simulations, many agents migrated to $area_1$ or $area_2$. Gradually, agents expanded their migration range with a temperature rise. In the later simulations, about 35 percent of the agents migrated to $area_4$. Our agents migrated from $area_0$ to $area_4$ within 3.76 generations on an average, which matches the fact that Monarchs migrate within 3 to 4 generations.

Fig. 2 shows the action decision diagram and the state decision diagram (variable nodes and outputs nodes appear in Section 1.2.1 and 1.2.2). X_0 is the next most significant information after X_1. The agent positively selects R and increases the number of agents because it can reproduce new agents only in the Rp state. The agent positively selects migration behavior, especially Ms, in the Dp state. It is clearly that the state is the agents, which we have newly focused on in this paper, is the essential factor for its behavioral decisions. On the other hand, X_5 and X_6 are the two most significant pieces of information for the agents in terms of deciding its states, while X_4 is third. This matches the behavior of actual Monarchs, which decide when to diapause and enter into a reproductive season on the basis of information about temperature and day length.

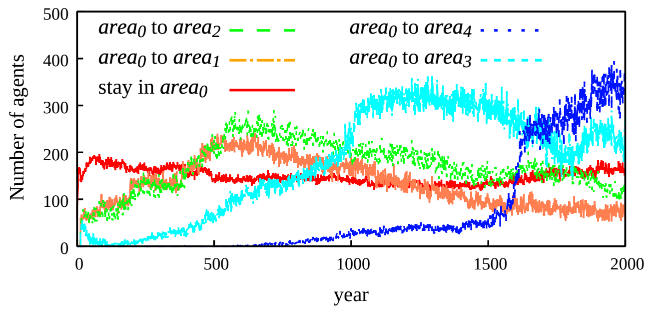

Fig. 1. The number of agents that stay in $area_0$ or migrate from $area_0$ to $area_n$ for 2000 years.

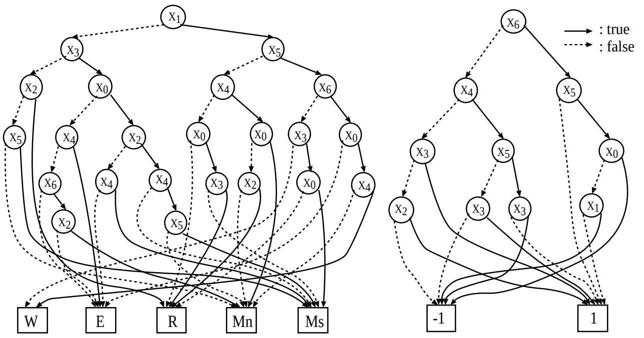

Fig. 2. Left: Action decision diagram (5-BDD), Right: State decision diagram (2-BDD).

2.2 Experiment 2.

We compared the annual migration of agents with that of actual Monarchs. Fig. 3 shows a time-line chart of migration. In the previous model, agents migrate from $area_0$ to $area_1$ between November and June of next year. Migrating toward colder areas in winter is completely different from the actual migration of Monarchs, which migrate south in fall and stay in wintering places to survive the cold winter. In contrast, agents proposed in this paper stay in $area_0$ from mid-December to February of next year. In spite of some differences in beginning and ending periods of migration, the migration cycle is similar to real one: the agents migrate north from spring to summer, migrate south from fall, and stay in $area_0$ from winter to next spring. We conclude that our proposed model extracts more significant key aspects of Monarchs' migration behavior than the previous model.

3 CONCLUSION

We presented an evolutionary model to simulate the multi-generational migration of the Monarch Butterfly. We build the model considering with the metamorphosis and the reproductive diapause. Agents emerged migration behavior similar to the multi-generational migration behavior of the actual Monarch. We show the advantage of our model by comparing with the result of the previous model.

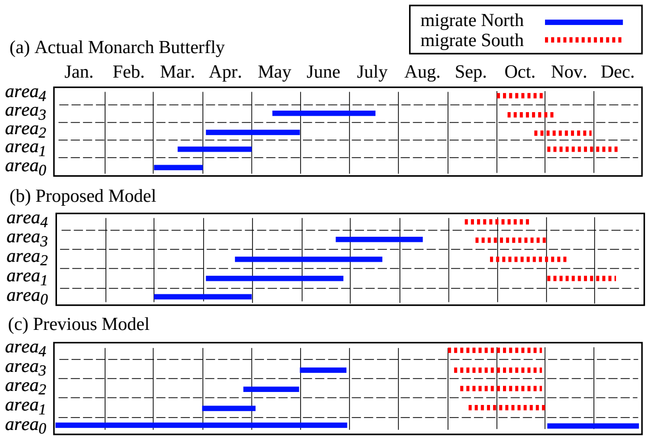

Fig. 3. Time-line chart of migration.

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