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A basic study on cooperative behavior of two butterflies inspired by quantum entanglement

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Abstract: Recently, the physical concept of quantum entanglement has been introduced into the two distant insects (butterflies) to cooperatively find each other by the previous study of J. Summhammer. According to his experimental results, we have confirmed that the two butterflies with quantum entanglement may need as little as half of the flight path of independent butterflies to find each other. However, the case where the learning factor, the length of a short straight flight and the threshold of the scent intensity are different between two butterflies has not been clarified in his previous study. Hence we have simulated the cooperation of two butterflies while changing the condition of these parameters. This paper describes the experimental results. We aim at the optimum modeling of cooperative relation of two individuals as the first stage, and the contents in this paper deserve the initial experiment in the case of two distant butterflies which must find each other.

Keywords: cooperative behavior, cooperative action, quantum cooperation, quantum entanglement

1 INTRODUCTION

Recently, the physical concept of quantum mechanical principle such as quantum superposition, quantum interference and quantum entanglement has inspired the information and computer science domain as well as the biology. For example, the physical concept of quantum interference has been brought to Genetic Algorithm by A. Narayanan et al. Quantum superposition has been brought to Evolutionary Algorithm by K.-H. Han et al., too. Regarding quantum entanglement, J. Summhammer has described the possibility of quantum entanglement in the biological domain [1]. He has introduced it into two insects (ants) to cooperatively push a pebble which may be too heavy for one ant, and has introduced it into two distant insects (butterflies) to cooperatively find each other. That is, each of ants/butterflies makes measurements on quantum particles to decide whether to execute certain actions. According to his experimental results, we have confirmed that the two ants with quantum entanglement, i.e., quantum-entangled ants, can push the pebble up to twice as far as independent (classical) ants, and the two butterflies with quantum entanglement, i.e., quantum-entangled butterflies, may need as little as half of the flight path of independent butterflies to find each other. However, the case where important parameters of two ants/butterflies are different each other has not been clarified in his previous study.

As for ants, we have clarified the relation between the force needed to push a pebble, the force of ant1 and the force of ant2 in our previous study. From the experimental results, we have proven that two ants with the bigger difference of force can push the pebble farther in competitive society in both classical ants and quantum-entangled ants [2].

As for butterflies, the relation between the learning factor, the length of a short straight flight and the fraction for threshold of the scent intensity is not yet clarified. In order to clarify the relation among these important parameters, we have simulated the cooperation of two butterflies while changing the condition of these parameters. This paper describes the experimental results. The optimum modeling of cooperative relation is expected by this study. We aim at the optimum modeling of cooperative relation of two individuals as the first stage, and the contents in this paper deserve the initial experiment in the case of two distant butterflies which must find each other.

2 OVERVIEW OF QUANTUM ENTANGLEMENT IN THE PHYSICAL DOMAIN USED IN QUANTUM-ENTANGLED BUTTERFLIES

In this paper we deal with the simplest kind of quantum entanglement. It is the correlation of the angular momentum between two particles of the same kind. The angular momenta of two such particles can easily be measured along different directions. The possible results are then "↑↑", "↓↓", "↑↓", and "↓↑", here "↑" and "↓" are *spin up* and *spin down*, respectively. Quantum theory can only predict the probabilities, $p_{\uparrow\uparrow}$, $p_{\downarrow\downarrow}$, $p_{\uparrow\downarrow}$, and $p_{\downarrow\uparrow}$, for these measurement results. An important state of quantum

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entanglement, which will be used in butterflies, is the so called *singlet state*. Here, the angular momenta of the two particles are always in the opposite direction each other. Symbolically, this state is written as

$$|\psi\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}. \quad (1)$$

The probabilities for the possible measurement results are

$$p_{\uparrow\uparrow} = p_{\downarrow\downarrow} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right), \quad (2)$$

$$p_{\uparrow\downarrow} = p_{\downarrow\uparrow} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right), \quad (3)$$

where α is the angle between the two chosen directions of measurement.

3 THE MODEL OF QUANTUM-ENTANGLED BUTTERFLIES FINDING EACH OTHER PROPOSED BY J. SUMMHAMMER

J. Summhammer showed the model that two distant butterflies find each other. Two butterflies, which are distant sufficiently each other, are located on the *x*-*y* plane as shown in **Fig. 1**. They can catch only information which is an intensity of scent emanated by other butterfly. Thereby for approaching each other, they must flight respectively to increase the intensity of the scent. The scent has the following character:

- The intensity of the scent emanated by each butterfly drops off as $1/r^2$ where *r* is the distance from the butterfly.
- The propagation of the scent is very much faster than the speed with which the butterfly, so that each butterfly can notice a change of intensity of the scent at once.
- The direction of the origin of the scent cannot be obtained from physical quantity involved in the scent.

3.1 Flight procedure of a modeled butterfly

As mentioned above, two butterflies can encounter by flying to the direction which increase the intensity of the scent. The algorithm for the flight toward the direction increasing the intensity of the scent is shown below:

[*Step 1*] Choose a direction for a short straight flight.

For the short straight flight, the butterfly chooses the direction randomly, but weighted with a probability distribution of directions. The probability distribution of directions is one which it considers appropriate in view of its experience of change of the scent intensity in the previous short flights. In the beginning, this probability distribution of directions is isotropic.

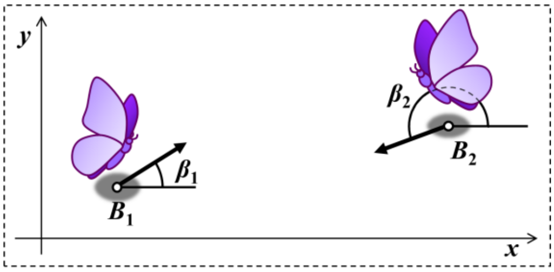

Fig. 1. The example of the flight directions β_1 and β_2 of the butterfly B_1 and the butterfly B_2 on the *x*-*y* plane.

[*Step 2*] Decide whether to really do the short straight flight, or whether to have a little rest.

Independent butterflies decide randomly either the short straight flight or the little rest, respectively. In this case, the probability of each behavior selected is constantly 1/2. On the other hand, the decisions of quantum-entangled butterflies come from quantum measurement which will be explained later. If the butterfly has decided the short flight, that performs a short straight flight of constant length l_f toward the chosen direction, go to *Step 3*. Otherwise, that is, if the butterfly has decided the little rest that does not perform any action, go to *Step 5*.

[*Step 3*] Judge whether the butterfly should fly back or not.

The butterfly measures the scent intensity and compares an increase from the last measurement with a certain threshold. The threshold is taken as a certain fraction f_t of the strongest increase $s_{d\max}$ of the scent intensity encountered in the short flights until then. If the increase s_d is below the threshold ($s_d < f_t \times s_{d\max}$), the butterfly judges this to have been a bad direction and flies back. The butterfly returns to the position before the short flight by flying back. On the other hand, if the increase is above the threshold, the butterfly judges this to have been a good direction and does not fly back.

[*Step 4*] Learn, i.e. update the probability distribution of directions.

Based on the above-mentioned judgment, the probability distribution of directions is updated using a learning factor *l*. When the butterfly had judged as a good direction, the butterfly enhances the corresponding probability weight by the factor $(1+l)$. This direction is then more likely to be chosen again in one of the next short flights. In contrast, when the butterfly had judged as a bad direction, the butterfly reduces the corresponding probability weight by the factor $(1+l)^{-1}$. This direction is then less likely to be chosen again.

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[*Step 5*] Repeat until the butterflies meet each other.

When the distance between two butterflies is less than a certain small value, it is concluded that the two butterflies met each other and this trial is ended. If the distance is still large, return to *Step 1* because the butterfly performs to the next short flight.

3.2 Behavior of the quantum-entangled butterflies

The difference between quantum-entangled butterflies and independent butterflies is shown when the butterfly decides either to really do the short straight flight or to have a little rest (above-mentioned *Step 2*). The independent butterflies decide randomly, whereas the quantum-entangled butterflies decide on the basis of a quantum measurement. The quantum-entangled butterflies share a large number of maximally entangled pairs of spin-1/2 particles, of which each butterfly holds one particle. Here the entangle state is the singlet state. The quantum measurement determines the value of the angular momentum of the particle along the flight direction which is chosen by the butterfly at *Step 1*. If the measurement result is "↑", the butterfly performs the short straight flight. If the result is "↓", the butterfly rests.

Here if we assume a butterfly B_1 chooses β_1 as the flight direction and a butterfly B_2 chooses β_2 as shown in **Fig. 1**, there are the following three possibilities.

Case 1: Both butterflies fly in the direction selected based on self-judgment respectively. This case happens with probabilities

$$p_{\uparrow\uparrow} = \frac{1}{2}\sin^2\left(\frac{\beta_1 - \beta_2}{2}\right), \tag{4}$$

according to Eq. 2.

Case 2: Both butterflies have a little rest. This case happens with probabilities

$$p_{\downarrow\downarrow} = \frac{1}{2}\sin^2\left(\frac{\beta_1 - \beta_2}{2}\right), \tag{5}$$

which is equal to $p_{\uparrow\uparrow}$.

Case 3: One butterfly flies and another rests. This case happens with probabilities

$$p_{\uparrow\downarrow} = p_{\downarrow\uparrow} = \frac{1}{2}\cos^2\left(\frac{\beta_1 - \beta_2}{2}\right), \tag{6}$$

according to Eq. 3.

Note that, when the difference between β_1 and β_2 gets closer to 0, the probability of Case 3 increases. In other words, when the quantum-entangled butterflies choose same direction which does not decrease the distance although both flight, only one butterfly flies frequently.

4 EXPERIMENTAL ANALYSIS

4.1 Method of the experiment

There are the following three important parameters characterizing behavior of the butterfly: the learning factor (l), the length of a short straight flight (l_f) and the fraction for the threshold of the scent intensity (f_t). About each of these three parameters, we have experimented by setting different value between two butterflies. In each following experiment, we have verified the relationship between the total flight distance until two butterflies encounter and the change of the target parameters.

Experiment 1: Varying the learning factor l for two butterflies.

We changed the learning factor l_1 of the butterfly B_1 from 1.00 to 0.00 in -0.05 steps, and also changed l_2 of the butterfly B_2 from 1.00 to 2.00 in +0.05 steps, respectively, where $l_1 + l_2 = 2.00$.

Experiment 2: Varying the flight length l_f for two butterflies.

We changed the flight length l_{f1} of the butterfly B_1 from 5.0 to 0.0 in -0.2 steps, and also changed l_{f2} of the butterfly B_2 from 5.0 to 10.0 in +0.2 steps, respectively, where $l_{f1} + l_{f2} = 10.0$.

Experiment 3: Varying the fraction f_t for the threshold of the scent intensity for two butterflies.

We changed the fraction f_{t1} of the butterfly B_1 from 0.60 to 0.20 in -0.01 steps, and also changed f_{t2} of the butterfly B_2 from 0.60 to 1.00 in +0.01 steps, respectively, where $f_{t1} + f_{t2} = 1.20$.

We used the default parameters shown in **Table 1** except the target parameters in each experiment.

4.2 Result of learning factor experiment

The experimental result is shown in **Fig. 2**. A solid line shows the average of each trial result by the two quantum-entangled butterflies. A dashed line shows the average of

Table 1. Default parameters used

The learning factor	1.00
The length of a short straight flight	5.0
The fraction for the threshold of the scent intensity	0.60
The direction chosen	16 directions evenly spread over 2π.
The initial distance of two butterflies	1600.0
The distance which can find the another (termination condition)	20.0
The number of trials	1000

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each trial result by the two independent butterflies. These are the same also at latter experimental results, which are **Fig. 2** and **Fig. 3**. The graph shows that the equality of the learning factor reduces the number of total flights to encountering of the two butterflies. Especially, this tendency is remarkable on the quantum-entangled butterflies. It is because the probability distributions of directions which change similarly with equal learning factor let the selection frequency of a direction related to cooperative behavior as shown in Eq.4 and Eq.5 increase.

4.3 Result of length of short straight flight experiment

The experimental result is shown in **Fig. 3**. The number of total flights decreases with increase of the difference of the flight length between two butterflies (l_{f2} - l_{f1}). Especially, this tendency is remarkable on the independent butterflies. It is because the difference of ability decreases the opportunity for disturbing each action of uncooperative butterflies. A large value of l_{f2} - l_{f1} extinguishes mostly the difference from the quantum-entangled butterflies. When one of the two quantum-entangled butterflies is provided the extremely small flight length, success or failure of their approach depends heavily on a behavior of another butterfly. Hence, probably cooperative behavior is no use.

4.4 Result of fraction for threshold of scent intensity experiment

The experimental result is shown in **Fig. 4**. In the case of independent butterflies, the number of total flights decreases with increase of the difference of the fraction for threshold of scent intensity (f_{t2} - f_{t1}) to f_{t1}= 0.27 and f_{t2} = 0.93. On the other hand in the case of the quantum-entangled butterflies, this tendency is not strong; the number of total flights is the minimum at the fractions: f_{t1}= 0.35 and f_{t2} = 0.85. Even if the quantum-entangled butterflies make a cooperative decision whether to fly or to rest, only one butterfly may judge that it is necessary to fly back when the difference of the fractions is quite large. Thereby, the meaning of cooperative behavior by quantum entanglement diminishes.

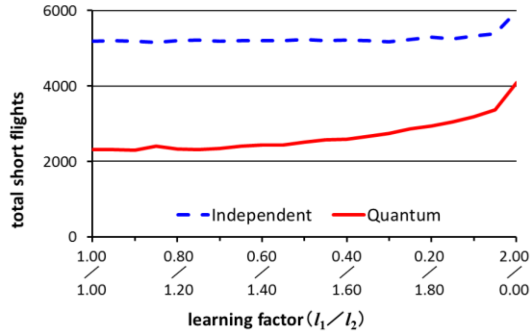

Fig. 2. Total number of short flights needed by the two butterflies to find each other vs. the learning factor l_1 and l_2.

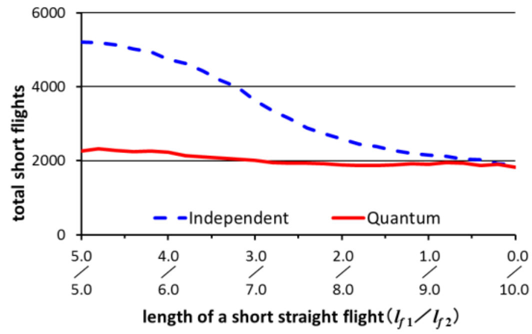

Fig. 3. Total number of short flights needed by the two butterflies to find each other vs. the length of a short straight flight l_{f1} and l_{f2}.

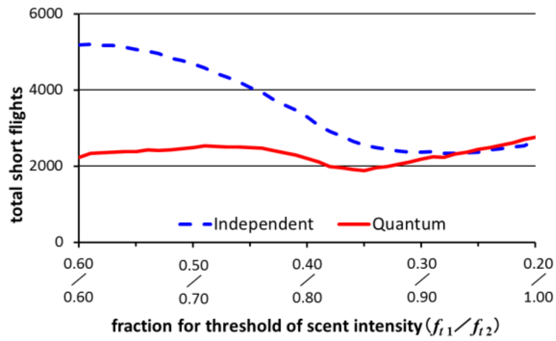

Fig. 4. Total number of short flights needed by the two butterflies to find each other vs. the fraction for threshold of scent intensity f_{t1} and f_{t2}.

5 CONCLUSION

In the model of the quantum-entangled butterflies finding each other, we have simulated the model while changing each the three parameter conditions in order to clarify the influence on the performance to find another butterfly. From the each experimental result, we have proven that the conditions to improve the finding performance are the more equivalent learning factor, the bigger difference of the length of a short straight flight, and the bigger difference of the fraction for the threshold of the scent intensity. However, when the difference of each parameter is too large, action of one butterfly is wasted and it may disturb cooperative behavior inspired by quantum entanglement.

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