Toward Realization of Highly Survivable Engineering Systems: A Simple Mathematical Model of Social Interactions among Vampire Bats

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Abstract

Vampire bats, which can die within three days if food is unavailable, can survive for over 10 years by developing a highly sophisticated social community in which they share food with each other. This food-sharing behavior occurs not only among blood relatives but also among unrelated individuals through self-organizing social relationships based on grooming behavior. Determining the mechanisms for generating of food-sharing communities in vampire bats will contribute to the design of new engineering systems with high survivability. We previously constructed a mathematical model that focused on the interrelation between food sharing and grooming behaviors, but this was still complex. In this study, we propose a simple network model to extract its essence and demonstrate through simulations that high survivability can be achieved under appropriate food sharing and grooming behaviors.

Introduction

Living organisms often swarm to exhibit macroscopic functions that cannot be realized by individual components (Camazine et al. (2003)). In these systems, altruistic behaviors, in which components of a swarm lose their own benefit for the benefit of others, often enable swarms to adapt to harsh environments such as environments with limited food resources, that is, enhance the survivability of swarms (Graham et al. (2017); Mikami et al. (2019)). We envisage that extracting the essential mechanisms that link intra-group altruism and group-wide survivability can make a valuable contribution to the development of new control schemes for engineering systems that can retain their functions in unpredictable and severe environments.

As an example of an altruistic species, we focused on the common vampire bat (*Desmodus rotundus*), also known as the blood-feeding bat, which is a social mammal that typically forms groups of eight to twelve adult females (Greenhall (2018); Wilkinson (1984)). Notably, these bats require regular intake of food to survive and can die within 3 days if they fail to acquire any food. However, they can survive for over 10 years by forming communities in which members that have fed regurgitate consumed food to sustain other starving members (food sharing), with the recipients reciprocating this behavior by providing food for the donors when the roles are reversed (Greenhall (2018)). Interestingly, in this regard, food sharing has been observed not only among blood relatives, but also among unrelated group members. Such communities, initially based on food sharing, gradually develop through other social interactions such as grooming (Wilkinson (1986)).

Although several mathematical models of the community of vampire bats have been proposed (Paolucci et al. (2006); Kubo et al. (2009); Witkowski (2007); Di Tosto et al. (2007)), they focused on either food-sharing or grooming behavior but did not discuss the interrelation between them. In contrast, we previously proposed an agent-based model to investigate the interrelation between food sharing and grooming and demonstrated through simulations that high survivability was achieved by establishing a food-sharing community (Mikami et al. (2020)). However, the complexity of this model makes it difficult to understand the essential mechanisms for the emergence of survivability. To address this issue, we propose a simple network model in which nodes and edges are regarded as individuals and social relationships between them, respectively. Through simulations, we demonstrated that survivability depends on the way social relationships are established.

The model

Each vampire bat was modeled as a node. Node i ($i = 1, 2, \cdots, N$) has satiety level $x_i(t)$ (≥ 0). When $x_i(t)$ becomes zero, node i dies; thereafter, it does not interact with the others, and $x_i(t)$ remains zero. The weight of an edge from node i to node j that represents the extent to which node i prefers node j is denoted by w_{ij} (≥ 0). Here, w_{ij} does not necessarily equal w_{ji}. For simplicity, other factors such as movement, age, sex, and blood relationships of the bats were not included. Food is provided externally to the nodes. Based on previously reported findings (Carter et al. (2020)), we assume that the community gradually develops through grooming and food sharing among nodes.

For the alive node i, the time evolution of $x_i(t)$ is given as

$$\frac{\mathrm{d}x_i(t)}{\mathrm{d}t} = -c_0 - c_1 x_i(t) + S_i(t) + \sum_{j \in alive} f_{ij}(t), \qquad (1)$$

where c_0 and c_1 are the positive constants. The first term on the right-hand side represents the basal metabolism. The second term is introduced to prevent divergence of $x_i(t)$. The third term $S_i(t)$ denotes the food intake from the environment. For the fourth term, $f_{ij}(t)$ represents food sharing between i and j, which is positive and negative when j shares food with i and vice versa, respectively. It is given by

$$f_{ij}(t) = w_{ji}(x_j(t) - x_i(t)) \;\; (\text{if } w_{ji}(x_j(t) - x_i(t)) > c_s),$$
$$f_{ij}(t) = -w_{ij}(x_i(t) - x_j(t)) \;\; (\text{if } w_{ij}(x_i(t) - x_j(t)) > c_s),$$
$$f_{ij}(t) = 0 \;\; (\text{else}) \qquad (2)$$

where c_s denotes a positive constant. These equations show that the node i with a higher $x_i(t)$ donates its food to node j. The upper and lower equations apply to the case where node i receives food from and donates it to node j, respectively. The amount of food to be shared increases as the difference in satiety level $x_i(t)$ between the pair increases and as the donor prefers the receiver.

For live nodes i and j, the time evolution of $w_{ij}(t)$ is described as

$$\frac{\mathrm{d}w_{ij}(t)}{\mathrm{d}t} = -c_2 w_{ij}(t) + c_3 \max\{f_{ij}(t), 0\} + c_3' \max\{-f_{ij}(t), 0\} + g_{ij}(t), \qquad (3)$$

where c_2, c_3 and c_3' are positive constants. The first term represents the decay. The second and third terms indicate that w_{ij} increases when node i receives food from node j and when node i donates food to node j. The fourth term represents the change in $w_{ij}(t)$ owing to grooming from i to j, denoted by g_{ij}, which is given by

$$g_{ij}(t) = c_5 \max\left\{ c_4 - \sum_{k \in alive} w_{ik}, 0 \right\}, \qquad (4)$$

where c_4 and c_5 are the positive constants. The term $\sum_{k \in alive} w_{ik}$ represents the extent to which node i has a social relationship with the others. When this term is larger than c_4, node i does not need to perform grooming, because it already has sufficient social relationships. In contrast, when this term is smaller than c_4, node i must perform grooming to develop new social relationships. Eq. (4) originates from the behavioral finding that bats with few food-sharing interactions tend to actively establish relationships with other community members (Carter et al. (2020)).

Simulation results

The simulations were performed using with 20 nodes. Among the 20 nodes, four nodes constantly obtained food from the environment, that is, $S_i(t) = A$ where A denotes the amount of food provided in a unit time. The other nodes did not obtain food from the environment; that is, $S_i(t) = 0$. The initial satiety level $x_i(0)$ was set randomly within the range of 10.0 and 11.9. The initial social relationship $w_{ij}(0)$ was set to 0. Simulations conducted in this study were 100000 time steps, which is sufficiently longer than the convergence times of $x_i(t)$ and $w_{ij}(t)$. The performance was evaluated based on the number of live nodes at the end of the simulation.

	$c_3 = 0.0$ $c_3' = 0.0$	$c_3 = 1.0$ $c_3' = 0.0$	$c_3 = 0.0$ $c_3' = 1.0$	$c_3 = 1.0$ $c_3' = 1.0$	$c_s \to \infty$
A=10.0	20.0 (0.00)	20.0 (0.00)	18.1 (0.30)	12.6 (2.33)	4.0 (0.00)
A=1.0	5.5 (0.92)	5.4 (1.20)	8.0 (0.00)	8.0 (0.00)	4.0 (0.00)

Table 1: Simulation results. The average value of the survived nodes after 10^5 time steps over ten trials are shown. Numbers in the brackets denote standard deviation.

To investigate how the development of social relationships through food sharing behavior contributes to the survivability of the whole community, cases of $(c_3, c_3') =$ (0.0, 0.0), (1.0, 1.0), (0.0, 0.0), and (1.0, 1.0), and no food sharing case $c_s \to \infty$ were simulated. Moreover, for each pattern, the cases of $A = 10.0$ and 1.0 were investigated to examine the non-starving and starving situations. Ten trials were conducted for each parameter set.

Table 1 shows the result. For $(c_3, c_3') = (0.0, 0.0)$ and (1.0, 0.0), all agents were alive when $A = 10.0$, whereas only about five agents were alive when $A = 1.0$. Thus, the adaptability to starving situations is insufficient. In contrast, for $(c_3, c_3') = (0.0, 1.0)$, eight agents could survive when $A = 1.0$, although the number of live agents was slightly less than the former two cases when $A = 10.0$. The videos in the case of $(c_3, c_3') = (0.0, 1.0)$ are shown at https://www.youtube.com/watch?v=7rk-T54_xes. When $A = 10.0$, nodes that can obtain food directly from the environment share food with several other nodes, which in turn share food with other starving nodes. In contrast, when $A = 1.0$, nodes that can obtain food shared food with several starving nodes. This food-sharing strategy emerged in a self-organized manner and increased the survivability of the entire community. The performance for $(c_3, c_3') = (1.0, 1.0)$ and $c_s \to \infty$ were worse than that for $(c_3, c_3') = (0.0, 1.0)$.

The above results suggest that an increase in the preference of a donor for a recipient is key to increasing the survivability of the whole community. However, it is still unclear whether the proposed grooming and food-sharing strategy is truly reasonable, because simulations under different conditions have not yet been investigated. We would like to change parameters systematically and to make a phase diagram, which will help clarify the essential mechanism for the emergence of survivability.

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