THE EFFECT OF ENVIRONMENTAL STRUCTURE ON THE UTILITY OF COMMUNICATION IN HIVE-BASED SWARMS

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ABSTRACT

1. INTRODUCTION

It may seem intuitively obvious that communication would be useful for hive-based swarms. Many insects that live togther in colonies or hives utilize some form of communication to aid in, for example, foraging; bees ([1, 4]) and, to some extent, ants ([6, 7, 5]) are examples. However, if environmental conditions are not right (e.g., if the envionment is sufficiently random), communication will yield little or no benefit (in this example because there is little useful information to share). There is experimental evidence for honey bees which indicates that in temerate habitats, where the degree of resource clustering is low, depriving the bees of their ability to reliably share information does not effect effect the amount of nectar they gather, whereas in tropical, more clustered environments, removing communication reduces nectar gathered [2]. Other simulation studies have investigated the utility of swarm communication for artificial tasks [8, 3]. This paper is an examination of communication in hive-based swarms in the biological setting, focusing on the effect environmental factors have on the utility of communication.

Our investigation utilizes a generational survival task to measure the benefit of communication. Agents forage for food, consuming energy in the process, and returning to a central "hive" to contribute any surplus. The resources of the hive determine when reproduction is possible, so it is in the best interest of the population to maximize the efficiency of foraging. The measure of performance is the size of the swarm surviving at the end of a simulation run. Each simulation begins with a swarm of fixed size (5 agents), making contributions to the hive (and subsequent procreation) necessary for good performance.

This paper presents our investigation of the utility of communication within hive-based swarms and the role environmental conditions play in determining the benefit. In this extended abstract, we are able to include only a brief description of the agent model and the setup and results of a series of preliminary simulations.

Figure 1. Random environment at cycle 1 (left) and cycle 10000 (right). Swarm members are labeled (hive_agent$n$), unlabeled dots represent food sources.

2. METHODOLOGY

2.1. Agent Model

The agents used are very simple reactive agents that simply target the nearest perceived food source and move directly toward it. Agents can consume only a fixed amount of food per cycle ($C = 50$), and are limited in the total they can consume ($T = 9600$); when the limit on total consumption is met, agents return to the hive. Each agent recalls the location of the food source it most recently visited (M), and if there is no food source within sensor range ($R = 200$), it instead targets the memorized food source and moves toward it. If there is no memorized food source (e.g., when the agent returns to a memorized location and the food source is gone), the agent begins foraging. Foraging behavior consists of moving in a random direction for a fixed number of cycles ($W = 200$). If no food source has been perceived after W cycles, the agent makes a random turn (1-45 degrees in either direction) and begins again.

Foraging and consumption rules:

- *Rule F1:* if no food source is perceived or memorized and energy $E >= T/4$, duty $D = forage$
- *Rule F2:* if no food source is perceived or memorized and energy $E < T/4$, $D = return\ to\ hive$
- *Rule F3:* if at least one food source is perceived and $E <= T$, move to nearest and consume it
- *Rule F4:* if no food source is perceived but one is memorized and $E <= T$, go to it
- *Rule F5:* if $E > T$, $D = return\ to\ hive$

Return-to-hive rules:

- *Rule R1:* if $E >= T/2$, continue to hive ignoring food
- *Rule R2:* if $E < T/2$ and no food perceived, continue to hive
- *Rule R3:* if $E < T/2$ and food perceived, $D = forage$

The hive's energy stores (H) are maintained by swarm members bringing food back to the hive. Agents consume energy as they move through the environment, but when they acquire a surplus of food, they return to the hive to contribute the surplus to the community pool. This pool is used for two purposes: food and reproduction. When agents forage without success, their own energy stores are depleted. Foraging agents can return to the hive and acquire energy there (if there is any). They can then return to their foraging duties. When an agent runs out of energy, it dies.

Agents can only reproduce when they are at the hive and the hive's energy stores are sufficiently high (procreation energy $P = 48000$). When an agent returns to the hive (either to contribute or consume food), if the energy threshold for reproduction is met, that agent can reproduce. Reproduction is asexual, and no mutation is employed; all agents are identical.

Hive rules:

- *Rule H1:* if $E > T/2$, contribute $E - T/2$ to hive store H
- *Rule H2:* if $E < T/4$, withdraw $min(T/2 - E, H)$
- *Rule H3:* if $H > P$, procreate

Given the above rules, the behavior of the swarm is predictable: at any given time some members will be foraging, wandering aimlessly throughout the environment looking for food. Others will be steadily moving between food sources and the hive and back, gathering food and bringing it back to contribute to the community store.

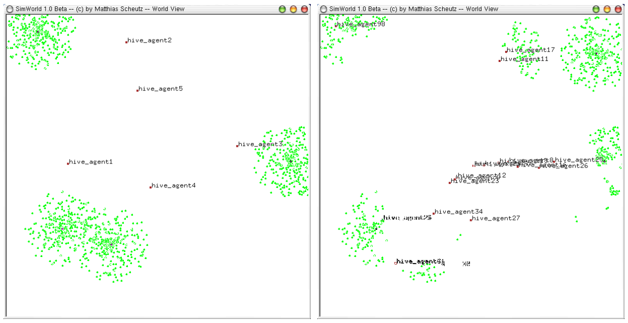

Figure 2. Cluster environment at cycle 1 (left) and cycle 10000 (right). Swarm members are labeled (hive_agent$n$), unlabeled dots represent food sources.

2.2. Communication

Communicating agents add to the basic model the ability to share with other agents the location of memorized food stores. Communication occurs only near the hive. When an agent returns to the hive with food, it communicates the location where the food was found to whomever else is near the hive. Those other agents can then choose to target the new source (if it is closer than their own target, or if they have no target and are foraging).

Additional hive rules for communicating agents:

- *Rule H4:* if memorized food source M, broadcast its location
- *Rule H5:* if broadcast location B nearer than M or $M = \emptyset$, $B \rightarrow M$

The behavior of communicating swarms is very similar to non-communicating swarms. Because communication takes place only near the hive, there is no widescale change in the action patterns. At times an agent will not return to the food source it just left, instead choosing a closer source given by another agent. More often, foraging agents take on a remote food source as a target. The communication mechanism meshes well with the agents' default behaviors: when agents are low on energy, they return to the hive. But they are low on energy just when they cannot find food. Thus, they are returning to the hive, and potential information regarding the location of food, exactly when they need to.

2.3. Environment Models

There are two environments in which we test the utility of communication: random and clustered. In the random environments, food sources are generated at random locations with probability 0.16 per cycle. This creates a steady influx

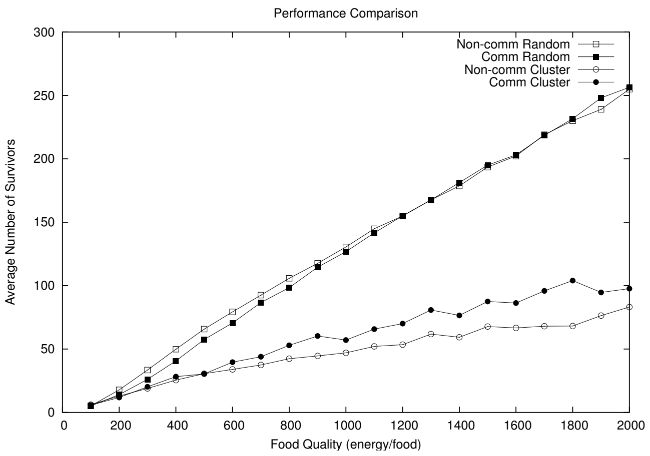

Figure 3. Comparison of communicating and non-communicating performance in random and clustered environments.

of energy into the environment without introducing structure. In the clustered environments, on the other hand, food sources are generated much less frequently (on average every 2000 cycles), and are placed at random locations in clusters of 320. The clusters of food sources are circular, 400 units in radius, and food sources are randomly placed within the cluster. Clustered environments introduce energy into the environment in spurts, with some structure. However, in all cases the amount of energy created on average is the same. Also, in all cases, food is generated outside of sensor range from the hive (i.e., agents cannot perceive food sources from the hive; they must remember or forage for it).

2.4. Experimental Setup

The experiments reported below each consist of 40 experimental runs in different randomly generated initial conditions. The simulations were performed in SWAGES, an artificial life simulation environment under development in our lab. The simulation environment is a continuous 2D world which is limited to a 3200 by 3200 square region. The same set of 40 initial conditions was used for each experiment in the same environment type, allowing us to compare directly between agent types. The results reported are averages over the 40 experimental runs that make up an experiment.

3. EXPERIMENTS AND RESULTS

We conducted extensive simulation experiments to explore the role of environment on the utility of communication. There are four basic configurations: non-communicating agents in random environments, communicating agents in random environments, non-communicating agents in clustered environments, and communicating agents in clustered environments. Each of these configurations was tested in environments where the food quality was varied from 100 to 2000 units of energy per food source, for a total of 3200 experimental runs.

The results of these experiments are presented in Figure 3. As predicted, the average number of survivors is greater in random environments than in clustered environments with the same net amount of energy. While the density of the food is lower, agents are more likely to come across food sources inrandom environments than in clustered ones, and hence less likely to die. Performance of communicating agents in random environments is similar to non-communicating agents, however, a two-way 2x20 ANOVA was conducted for *agent type* (non-communicating and communicating) and *food quality* (100 to 2000) as randomized variables and *average survivors* as dependent variable for random environments. There were highly significant main effects for both agent type (F(1,1) = 23.151, $p < 0.001$) and food quality (F(1,11) = 113062.150, $p < 0.001$). The latter indicates, as expected, that as food quality increases the average number of survivors also increases. The former indicates that there is a difference between communicating and non-communicating agents in random environments. Additionally, there is a highly significant interaction between agent type and food quality (F(1,11) = 2.9153, $p < 0.001$).

The difference between communicating and non-communicating performance appears to originate in the first half of the results (food quality from 100 to 1000), where non-communicating agents outperform communicating agents. `In fact, if I run 2x10 ANOVAs on the first and second halves, the difference is significant for the first half but not the second half; should those ANOVAs go in here?` For higher food qualities, performance is similar, with some indication that communicating agents may be gaining ground. Further studies extending the range of food qualities examined will show whether there is a pattern emerging.

In clustered environments, an analogous two-way 2x20 ANOVA was conducted for agent type, food quality, and average number of survivors. Again, there were highly significant main effects for agent type (F(1,1) = 63.485, $p < 0.001$) and food quality (F(1,11) = 993.529, $p < 0.001$), and a highly significant interaction between agent type and food quality (F(1,11) = 27.624, $p < 0.001$). The slight downturn of communicating agents when food quality is 1900 may indicate that performance is once again converging or may be a local effect; further investigation extending the range of food qualities tested will settle the question.

The most interesting effect here is the apparent diverging of communicating and non-communicating agents in clustered environments. It may seem that the advantage of communication should be constant, much as it appears to be in the random environments. However, the difficulty of foraging does not decrese as food quality increases; non-communicating agents still need to come across food in their wanderings. Increasing the value of the food once found does increase non-communicating agents' performance, but not as much as communicating agents'. In other words, increasing the quality of food sources not only boosts the benefit of finding a food source, it also increases the benefit of sharing information about food sources. Thus, communicating agents increase performance at a faster rate.

4. CONCLUSION

This paper presents an investigation of the effect of the environment on the utility of communication in hive-based agents. Little is known about the conditions that must be met in order for communication to be worthwhile, yet we know that it has evolved in many colony insects. In order to better understand the food configurations most conducive to communication evolving, we created simplified but biologically plausible agents and tested them in a variety of environments, comparing the performance of agents with and without communication. We found that when resources are clustered throughout the environment instead of randomly distributed, communuicating agents enjoy a significant advantage over non-communicating agents when the quality of the food sources is sufficiently high. Furthermore, as the quality increases, so does the communicating agents' advantage.

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