Animal and Machine Intelligence – Project Report

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Abstract

Individual and colony ant behaviors, involving high sociability, chemical-based communication, swarming in search of food, the need for camouflage, and organization into mixed societies, can serve as inspiration for distributed systems. Collections of small robots are starting to implement some of these behaviors. This paper investigates the pros and cons of using these behaviors as the basis for a hypothetical robotic distributed house cleaning system.

Introduction

This document reports on the pros and cons of using ant behaviors as inspiration for building a distributed robotic house cleaning system, tentatively called the KrumBum. This system must clean as well as a standard vacuum cleaner, by using a large number of autonomous micro-robots acting cooperatively in parallel. The initial prototype need only clean hard flat floor surfaces, but the final production version will also need to clean carpets. At pre-established times, such as the middle of the night, the KrumBum units will leave their "nest". In as short a time as possible they will remove all the crumbs and dust from designated parts of the floor. They will carry the debris back to the "nest" for disposal. I will report on a sampling of potentially useful ant behaviors, will discuss several existing small robots that could possibly be adapted to implement these behaviors, will briefly compare ants and robots, and will discuss some reasons why it would be very difficult to use ants themselves as part of the KrumBum system and the implications of this for the use of collections of small robots.

Ants – Individual and Colony Behaviors

A characteristic feature of all ant species is their high sociability. Ants are always found in colonies containing between a few hundred and several million individuals. In the view of Hölldobler and Wilson (1994, p.9) "the competitive edge that led to the rise of the ants as a world-dominant group is their highly developed, self-sacrificial colonial existence". Working together within the colony, ants tend their young, defend themselves against other ants and insects, and cooperate to find food. If one ant leaves some task undone, another ant will almost certainly complete it. Some ants such as the Saharan desert ant Cataglyphis are solitary foragers (Wehner et al., 1996) but return to the colony nest with the food they find. At the other extreme are army ants that forage as a swarm and are never away from their nestmates. Under experimental conditions, when a group of a few thousand workers is cut off from the main swarm, the army ant social instinct is so strong that they will follow each other in a circular pattern. After 30 or more hours, this "circular milling" ends with the death of all the ants as they succumb to starvation (Schneirla, 1971).

Ant species vary in their use of vision. The Cataglyphis desert ant has a sophisticated visual system that allows it to use landmarks for navigation while foraging away from the nest (Wehner, 1996). While all army ants have some sensitivity to light, many species have no eyes and use light only as a time-of-day signal (Schneirla, 1971, p.28-29). As for communication between ants using vision, "not a single example has yet been solidly documented" (Hölldobler & Wilson, 1990, p.259).

Odor, the detection of pheromone and other chemicals, is the primary means by which ants distinguish between nestmates, food, and otherwise sense aspects of the environment. Ants also release a variety of chemicals in minute quantities from special glands. These chemical signals trigger response behaviors in other ants, which Hölldobler and Wilson (1990, p.227) have organized into twelve functional categories including alarm, simple attraction, recruitment, recognition, various group effects, and territorial marking. The desert ant is unable to use odor as part of its foraging behavior because the heat immediately evaporates any chemical (Lambrinos, 2000), and it must instead rely on vision. The army ant foraging pattern would not be possible in an open desert region (Schneirla, 1971, p.10).

Chemical signaling is not point-to-point. One ant does not communicate directly with one other ant, in contrast with symbolic linguistic communication in humans. Instead, communication is through the environment. One or more ants release a chemical into the environment which may subsequently be detected by other ants or individuals of other species. If an individual is within range of a chemical signal diffusing through the air, and if it has a hard-wired behavior that is triggered by that signal (but dependent partly on other current environmental and internal brain states), that ant will engage in that behavior.

In 1959 Grassé introduced the concept of stigmergy to explain a coordination paradox. Social insects appear to behave strictly as individuals, and yet somehow their individual actions result in complex global effects such as nest building and foraging patterns. Theraulaz and Bonabeau (1999) summarize the important principle of stigmergy as follows:

> Traces left and modifications made by individuals in their environment may feed back on them. The colony records its activity in part in the physical environment and uses this record to organize collective behavior. Various forms of storage are used: gradients of pheromones, material structures (impregnated or not by chemical compounds), or spatial distribution of colony elements. Such structures materialize the dynamics of the colony's collective behavior and constrain the behavior of individuals through a feedback loop. Stigmergy also solves the coordination paradox: Individuals do interact to

achieve coordination but they interact indirectly, so that each insect taken separately does not seem to be involved in a coordinated, collective behavior.

High sociability, limited use of vision, use of odor, and the general concept of stigmergy, suggest some basic principles that should be adopted in the design of the KrumBum housecleaning system. Individual units must work closely together using some form of stigmergic coordination, control and communication. There should be no need for central control, but there does need to be constant interaction and feedback through the environment. The proper mode for such interaction is chemical (or some high-tech equivalent) rather than visual.

This paper will now investigate several specific behaviors linked to specific ant species.

Swarming in search of food

Army ants swarm in search of food. The pattern formed when foraging differs between species. Some species, such as Eciton hamatum advance outwards in multiple columns, while Eciton burchelli and Dorylus driver ants adopt a pattern that includes a single broad swarm front (Hölldobler & Wilson, 1990, p.576). This section will focus mostly on the E. burchelli pattern.

E. burchelli army ants continuously cycle through two phases, a statary phase to allow time for reproduction, and a nomadic phase. Each day during the nomadic phase, the swarm moves in a different direction away from that day's temporary bivouac. It starts along a thin base column which some 20 meters from the bivouac opens up to form a swarm front that reaches some 20 meters across. The base column and swarm front are connected by fan columns. The pattern keeps the nearly blind ants within the necessary close proximity to each other, allows for total exploitation of prey in some contiguous space along the ground, and allows for food to be carried back to the nest at the same time the front is moving forwards. Workers take turns running at the front of the swarm. They lay down small quantities of pheromones to guide the others in the same direction. This pattern is a good example of chemical-based stigmergy in action.

A theoretical model (Deneubourg et al., 1989; Franks et al., 1991) predicts that the raiding pattern, column, swarm or intermediate, results partly from different food distributions on the ground. Distribution as small randomly placed food items produces a swarm pattern, while larger regions of food produces a more column pattern of raiding. Solé et al. (2000) followed with a similar simple model involving discrete ant units moving over a 2D lattice. Parameters in their model are: (1) amount of pheromone laid down as an ant moves outward in search of food, (2) amount laid down when returning with food, (3) evaporation rate of the pheromone, (4) probability of movement, and (5) direction of next movement. The parameter space was searched for best-fit solutions using a search algorithm. A solution was found that could produce an E. hamatun raid pattern, an E. burchelli pattern, or an intermediate pattern, by using very similar values for parameters 3, 4 and 5, while varying 1 and 2.

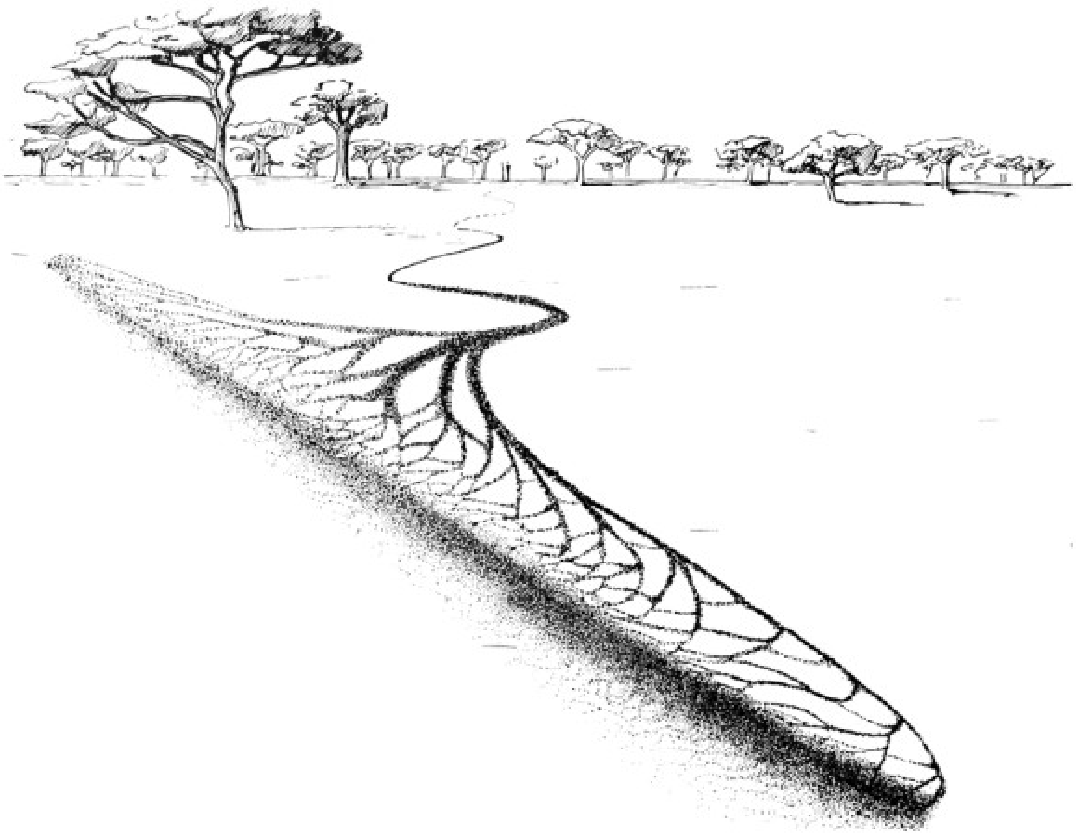

Figure 1 – Characteristic driver ant swarm raiding pattern (Hölldobler & Wilson, 1994, drawing by Katherine Brown-Wing), similar to the E. burchelli pattern.

The E. burchelli raid pattern is similar to what would likely be needed by the KrumBum. A diagram (Figure 1) of a large number of foraging driver ants (Hölldobler & Wilson, 1994, p.109) looks a lot like a vacuum cleaner. The broad leading edge looks like a wide floor attachment, while the thin line back to the nest is like a hose carrying the dust back to the canister. The behaviors by which driver and other army ants strip a roughly rectangular area of food may help to inspire ideas for the collective behavior of KrumBum micro-robots. If the Deneubourg et al. hypothesis is correct, the relatively even distribution of dust on a floor suggests this more swarm-like E. burchelli raid pattern.

Dirt as a form of camouflage

Basiceros manni, and other related species of ants, are masters of camouflage. Their bodies are covered with two types of hair that accumulate soil. This adaptation, plus their innate brownish coloring, slow movement, and group ability to freeze into one position for minutes at a time, make them difficult to detect by birds and other sighted predators. Hölldobler and

Wilson (1986) propose that longer erect “brush” hairs gather soil particles as the ants move, while shorter “holding” hairs retain it close to the body (see Figure 2). In terms of the KrumBum practical application, using dirt-collecting and -trapping hairs might be particularly effective in hard-to-reach places, and along walls where dust tends to collect.

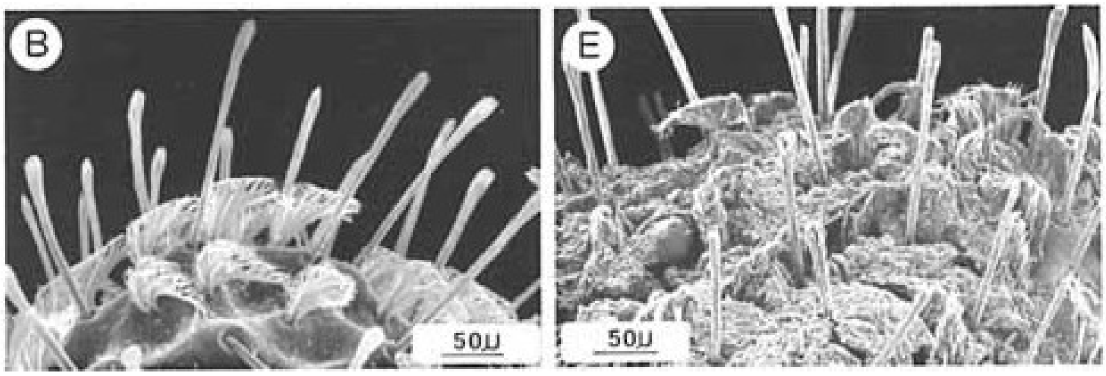

Figure 2 - (B) shows the pristine longer "brush" hairs and shorter "holding" hairs of a young worker. (E) shows the accumulated soil on an older worker (Hölldobler and Wilson, 1986).

Mixed societies

Many ants live in mixed societies involving ants of different castes, ants of different sizes, and mixtures of ant and non-ant species. One characteristic ant adaptation, at least in the eye of human beholders, is a caste system in which each caste assumes certain roles, although the roles are somewhat fluid (Hölldobler and Wilson, 1990, p.298+). Traditionally-recognized categories include queen, male, and various workers distinguished largely by size. The main role of a queen is production of eggs, while short-lived males contribute sperm. Female workers may vary considerably in size and may be designated as major, media, or minor.

Leaf-cutter ants have evolved an assembly line strategy involving a wide range of ant sizes (Hölldobler and Wilson, 1994, p.111+). The larger majors cut and carry leaves back to the nest; the smallest minors tend the fungus gardens within the nest. A variety of separate tasks must each be performed by an ant of the appropriate size and strength.

Many ant colonies include multiple species, involving parasitic, slave or domestication-like relationships between species. The simplicity of the ant chemical-based stigmergic communication system makes parasitic roles possible. Many species have successfully decoded and hijacked the chemical language used by another species and have taken on a controlling role. Merely by acquiring the colony odor, many parasitic beetles and other non-ant species “are readily admitted to the company of the ants, who are then inclined to feed, wash, and carry them bodily from place to place” (Hölldobler and Wilson, 1994, p.123). Ants recognize each other based *only* on odor, in stark contrast to our own species’ rich mix of visual, auditory, tactile, odor, and taste cues.

There are three useful concepts here for the KrumBum. (1) Several specialized worker castes could each perform different roles in the cleaning process. (2) Each caste could include a variety of sizes. Larger units could collect relatively large particles from the floor, a B. manni-type caste could collect smaller particles on their hair, and one caste could roll a round sticky caste along the floor to collect fine dust (much as ants roll their own larvae in the nest). (3) A controller caste, essentially a different species, could manipulate the stigmergic language of the worker castes. The system would be developed by first creating or evolving the worker roles and a common chemical-based language. The resulting behaviors would then be controlled and constrained for human goal-directed purposes by having the controller species learn to hijack the chemical signals. Each species could be separately developed or co-evolved using such techniques as evolutionary robotics, genetic algorithms, and neural networks.

Mini Mobile Robots

Several groups are actively developing what Caprari et al. (1999) refers to as mini mobile robots (MMR). MMRs are small, are designed to interact with each other, and are conceptualized as having similarities with social insects especially ants.

Alice

Each individual in the Alice family of mini mobile robots (Caprari et al., 1999) is a one-inch cube (Figure 3). An Alice robot has two bidirectional watch motors each of which controls one of two wheels. An onboard microcontroller with 8K words of memory controls behavior by reacting to signals from its IR proximity sensors and its tactile sensors, by building a map of its world to assist in navigation, by sending signals to the two motors, and through interactions with humans over IR, TV and radio links. There are plans for chemical sensors.

Figure 3 - An Alice "sugar-cube"-sized robot.

An Alice is powered by a battery. Research with Alice has pointed out a number of real-world technical issues with such small robots. Power management has been a fundamental issue (Caprari et al., 1999). Navigation is difficult because of uneven floors and wheel slippage.

Alice researchers are actively investigating collective behavior, to understand "the underlying methods to control swarms of decentralized minirobots" (Caprari et al., 1999). To date, two teams with three Alices per team have been able to play soccer on an A4-sized sheet of paper.

Swarm-bots

An s-bot is a simple battery-powered insect-like mini mobile robot (MMR), but larger than an Alice. Each s-bot has wheels and tracks controlled by motors, IR proximity sensors, plus force, torque, humidity and temperature sensors. It can communicate with other s-bots, sending signals using eight color LEDs organized into a ring, and receiving signals through light sensors and an omnidirectional camera. Behavior is controlled by multiple PIC processors sharing 64M RAM and 32M flash memory, much more processing power than found on an Alice. A swarm-bot is a collection of s-bots. A key feature of an s-bot, lacking in Alice, is a gripper that allows two or more s-bots to rigidly connect to each other, one way of creating a swarm-bot.

Leurre

The LEURRE project, French for "lure", hopes to produce mixed societies in which social insects and robots would interact and communicate (LEURRE web page). Robots with specific controlling behaviors would be inserted into an insect colony with the intent of triggering some new emergent global pattern. The project intents to use an existing MMR such as the Alice, and will concentrate to begin with on cockroaches rather than ants because they feel there is too much of a size difference between an ant and Alice. In initial work (Jost et al., 2004) an Alice has been successfully programmed to reproduce cockroach-like behaviors. The concept of using a human-produced "lure" has been successfully employed in a bee hive. A simple mechanical device, a "robot bee" that actually looks nothing like a bee, performs a waggle dance that successfully directs the observing bees to a specific site in search of food (Michelsen, 1989). The LEURRE concept is much the same as proposed in the "Mixed societies" section above.

Electronic nose

An electronic nose detects and identifies chemicals in the physical environment. Applications include quality control by detecting the odor of coffee, beer and other products, detection of illicit drugs, and detection of micro-organisms. Chemicals detected include small molecules of the sizes typically used by ants for communication, coordination and control (Hölldobler &

Wilson, 1990, ch.7). Hayes et al. (2003) are actively investigating detection of odor plumes by the Moorebot robot fitted with a penny-sized odor sensor (Figure 4).

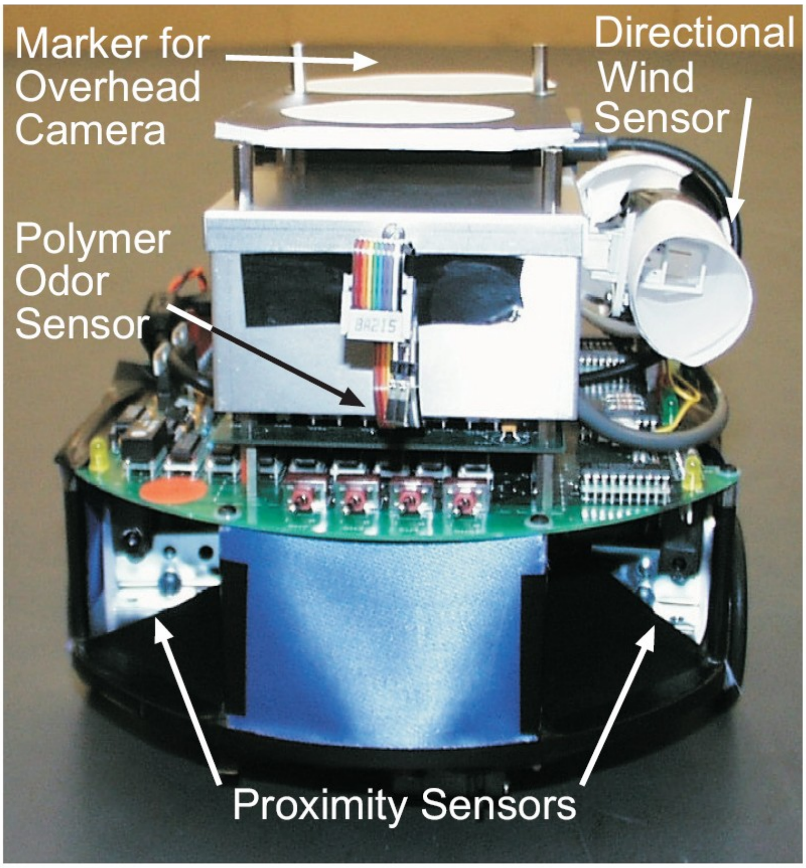

Figure 4 - Moorebot robot fitted with a polymer odor sensor (electronic nose), and other sensors. (Source: http://www.coro.caltech.edu/people/alcherio/papers/Robotica_03.pdf)

Other robotics work

I have investigated the interesting work on ants and robots underway at the AILab in Zurich (Lambrinos, 2000; Hafner & Möller, 2001). Much of this work concerns the sighted desert ant and its landmark navigation abilities. As discussed elsewhere in this paper, I believe that this work cannot provide much of immediate use for the KrumBum system because of its focus on solitary navigation, and on vision rather than odor.

Comparison of Ants and Mobile Mini Robots (MMRs)

It is useful to compare some key features of ants and mobile mini robots, specifically the Alice MMR.

Source of energy: Ants have to eat in order to produce energy, and as part of their energy cycle they produce material waste. Alice uses a battery, a "clean" source of energy in which all the messiness of energy cycles is located somewhere else. Each Alice does produce a small amount of waste heat.

Mode of production: Ants (but usually just the queens and males) participate in their own reproduction, and must set aside time and energy to do this. The activity cycle of individuals and of the colony is altered by the need to reproduce, especially noticeable in the swarm/nest cycle of some species of army ants. Alice is produced by an external process.

Activity: Ants are always active or at least always turned on. Alice can be switched on and off.

Mode of transport: Ants use six legs activated by muscles under the control of a brain with up to one million neurons. Alice uses two wheels activated by two bidirectional watch motors under the control of a microcontroller with 8K of memory.

Sensors: Ants sense (and produce) chemical odors which serve as signals that activate behaviors. Some species have varying levels of vision. Alice has IR proximity sensors, and tactile sensors (plus various ways of communicating with human controllers). Other robots have been fitted with chemical odor detectors.

Behaviors: Each ant species has some ten to twenty identifiable behaviors, adaptively shaped by evolution. Alice has three behaviors: obstacle avoidance, wall following left, and wall following right.

These differences between ants and MMRs all have implications for development of the KrumBum.

Issues & Discussion

Robots have a ways to go before they can match natural ant capabilities. Why not use ants themselves as the working units in the KrumBum house cleaning system? This is an intriguing idea, but there are some issues, as there would be with using any embodied creature that is situated within a specific environment, and some of these issues may carry over into potential robotic solutions.

Army ant colonies go through a regular cycle that includes a two-week reproduction phase when the colony's energy goes into replacing its lost units rather than raiding. Chemical signals may take on different meanings during these times, and it may not be possible to rally the army just because a dirty floor needs attention.

Ants eat what they gather. Dust and particles in the house, and not the floor in general, would need to be given the right odor so that ants would think they are food. It is uncertain how either that which needs to be carried away (dust and particles) and that which needs to stay in place can be marked so that ants will only remove the "food". Back at the nest the collected "food" would need to be replaced by something genuinely nourishing. At the other end of the food cycle, ant droppings could be a problem. There's no point having a house cleaning system that contributes as much waste as it collects.

These examples point out the difficulties of harnessing just one part of a natural cycle or behavior. Robots may be able to avoid problems associated with natural cycles, but it is not clear how they would get around the problem of distinguishing "food" from "non-food".

There are parallels with the search for artificial intelligence. On the one hand, can we abstract something called human intelligence and recreate it using different hardware, or can it only exist within embodied chemically-real humans situated within a higher primate environment? On the other hand, can we abstract elements of intelligent adaptive ant behavior, and either recreate it with the same hardware but in a quite different environment, or can we recreate it in different hardware?

Conclusion

Ants can inspire us with ideas on how to build systems of many small homogeneous or heterogeneous units interacting stigmergically over time. The chemical signaling used by such systems may allow a point of control that will allow hijacking of these systems to perform human purposeful tasks. Whether ants themselves can be harnessed, or whether only artificial robots can be sufficiently domesticated, must await further research.

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