Pheromone Robotics

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Abstract: We describe techniques for coordinating the actions of large numbers of small-scale robots to achieve useful large-scale results in surveillance, reconnaissance, hazard detection, and path finding. We exploit the biologically inspired notion of a "virtual pheromone," implemented using simple transceivers mounted atop each robot. Unlike the chemical markers used by insect colonies for communication and coordination, our virtual pheromones are symbolic messages tied to the robots themselves rather than to fixed locations in the environment. This enables our robot collective to become a distributed computing mesh embedded within the environment, while simultaneously acting as a physical embodiment of the user interface. This leads to notions of world-embedded computation and world-embedded displays that provide different ways to think about robot colonies and the types of distributed computations that such colonies might perform.

Keywords: robot swarm, emergent behavior, distributed control, multi-agent systems

1. Introduction

Consider a scenario in which a robot lands on a planet and needs to quickly locate certain resources. The mother ship disgorges hundreds of thousands of tiny crawling or flying robots (Figure 1a). Using simple attraction/repulsion behaviors, these robots quickly disperse, using their weak line-of-sight communication to keep contact with only their closest neighbors (Figure 1b). Upon detection of the resource, a robot emits a "virtual pheromone" message signaling the discovery. This message is diffused

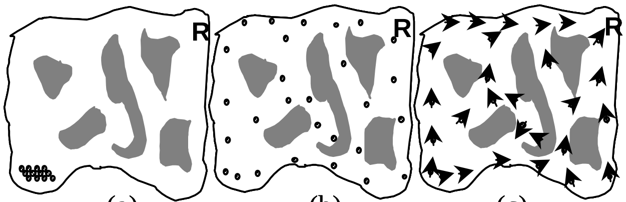

Figure 1: **Robots disperse throughout an area to become an embedded computing grid and an embedded display for finding the shortest path to a resource.**

throughout the distributed mesh of robots, propagating only along unobstructed paths. Ultimately, the message makes its way back to the mother ship. Since each robot remembers the direction from which it received the message, the robots now collectively serve as a distributed array of guideposts (Figure 1c) that can be followed by a more powerful mining robot. If the probe is manned, members of the crew can use augmented reality displays to view the robot swarm as a world-embedded display, showing the local gradient that leads to the resource. Following this gradient provides the shortest unobstructed path.

Emerging technologies in micro machining and MEMs hold the promise of creating extremely small robots that could make the above scenario a reality. Such robots, although limited in size and power, can work together in large numbers to conceivably accomplish a wide range of significant tasks [5],[7],[10],[17], including surveillance, reconnaissance, hazard detection, path finding and payload conveyance.

Coordinating and interacting with very large numbers of robots involves issues not encountered when dealing with one or a few robots [2],[8]. Coordination schemes that require unique identities for each robot, explicit routing of point-to-point communication between robots, or centralized representations of the state of an entire swarm can be overwhelmed when dealing with extremely large numbers.

We are inspired by techniques used by ants and termites for communication and coordination [4],[9]. We implement "virtual pheromones" using simple transceivers mounted on each robot. Like their chemical counterparts, our virtual pheromones facilitate simple communication and emergent coordinated movement with only minimal on-board processing. But virtual pheromones go a step further, transforming a robot swarm into a distributed computation grid embedded in the world. This grid can be used to compute non-local information about the environment such as bottlenecks and shortest paths, in ways that are foreign to insect colonies.

2. Virtual Pheromones

The design of virtual pheromones preserves some of the essential properties of natural pheromones that make them effective in facilitating group organization. (1) Pheromones are locally transmitted without specifying a recipient. This obviates the need for unique identities that are impractical in large groups [8]. (2) Pheromone diffusion gradients provide important navigational cues and also encode useful information about barriers in the environment that block pheromone propagation. (3) Pheromones decay over time, which reduces obsolete or irrelevant information.

Virtual pheromones are not faithful copies of chemical pheromones, for several practical reasons. For example, natural odors diffuse in patchy plumes whose concentration does not fall off uniformly with distance or time, as do our virtual pheromones. Virtual pheromones are transmitted at a known intensity so receivers can reliably estimate distances on the basis of signal strength alone. Second, if an originating source for a virtual pheromone moves, the gradient will adjust quickly without the persistence of chemical pheromones. Third, virtual pheromone messages can contain optional data that can be used in distributed computations as discussed in Sections 3 and 5.1.

3. World embedded computation

Most approaches to path planning and terrain analysis operate on an internal map of terrain features [15],[16]. Our approach is to embed processing elements into the terrain, actively sensing local terrain features. Global properties such as shortest routes, blocked routes, and contingency plans can be computed in a robust, distributed manner, with each member of the population of simple processors contributing a small piece of the result.

Traditional approaches perform the steps of sensing, data transmission to a central point, and map generation before the data can be processed. This is especially disadvantageous when the environment is rapidly changing. Pheromone robots (or *pherobots*) require no distinct step of map generation. Instead they act as a distributed set of processors embedded in the environment, performing both sensing and computation tasks simultaneously.

Inter-robot communication is implemented via line of sight InfraRed (IR) signaling rather than wireless, because it results in a communications grid that embodies mobility costs in its connectivity structure. Rather than trying to overcome communication loss due to obstacles, we exploit this effect to determine optimal traversal paths. In fact, our rules for message propagation provide a distributed version of the wavefront propagation method used in Dijkstra's shortest-path algorithm [6].

Figure 2: User's view of a pheromone gradient as seen through an augmented reality display

4. World Embedded Display

Pherobots implement an efficient and versatile distributed computer. In some applications the results of the computation are sent back to the user via relayed messages. But the real novelty of the system is when the robot swarm acts as a distributed display embedded within the environment. In effect, each robot becomes a pixel. The robot's position within the environment provides context to interpret the meaning of the transmitted information.

As an example, consider the notional view in Figure 2. Here, the robot swarm has dispersed, and a pheromone gradient has been established. A user seeking to follow that gradient needs only to be able to see the local gradient vector at each robot location. One way to read the distributed display is to use an augmented reality (AR) system. AR refers to the visual presentation of information, in geometric registration with true objects seen in the environment. We have created a portable system that can detect signals emitted by each robot, using a see-through head-mounted display (HMD) [3].

5. Methods and Techniques

5.1 Virtual Pheromones

Virtual pheromones are implemented by messages relayed from robot to robot, with specific features that enable them to travel in decaying waves from the origination point. Atop each robot is a set of eight radially-oriented directional InfraRed (IR) transmitters and receivers (transceivers) as shown in Figure 3. IR is directional, it propagates by line of sight, it is easily modulated, and it loses intensity with increased distance from the source. Directionality is needed to encode pheromone gradients, line-of-sight propagation is needed to assure that pheromone gradients do not pass through obstacles, modulation is needed to encode pheromone type and other data, and distance drop-off is needed to allow robots to estimate their distance to the sender.

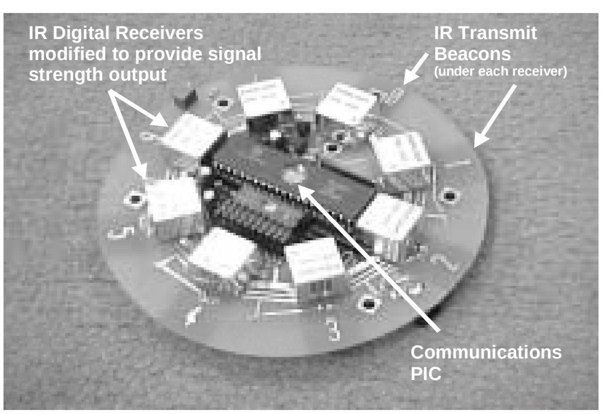

Figure 3: Transceiver for virtual pheromones

A virtual pheromone is encoded as a single modulated message consisting of a type field, a hop-count field, and a data field. The type is an integer that identifies a unique pheromone class. The originating robot sets the hop-count to an integral number of times the message is to be relayed. The data field may be used to optionally transmit a few bytes of data. Upon receipt, the hop-count field is decremented and the message relayed in some or all directions. If a robot receives the same type of pheromone from

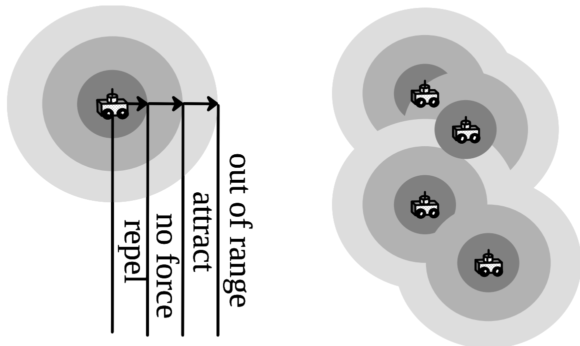

Figure 4: Decrease of pheromone intensity with distance is the basis for robot attraction and repulsion.

multiple directions, only the message with the highest hop-count value is selected for re-transmission. Pheromone gradients may be altered without the need for physical movement of the robots. For example, data in the message can specify which ports should retransmit the message with respect to the receiving port, causing messages to move through the swarm in certain geographic directions. In a sense, our robot collective is a sensor network similar to JPL's Sensor Webs[12], with the added benefit of self-emplacement.

5.2 Robot Movement Primitives

Our primary robot behavior primitives are repulsion and attraction, using only the strength of received virtual pheromone messages to determine the proximity of neighboring robots. Obstacles are sensed when pheromone messages bounce off them. The robot control system generates a repulsive force from very close robots and obstacles, which prevents collisions and ensures that robots will spread out. Robots are attracted to each other to stay in communications range. Appropriately combining the elemental attraction and repulsion behaviors can produce a variety of emergent group behaviors [1]. Two important emergent behaviors that are central to our approach are the "gas expansion" model and the "guided growth" model.

The gas expansion model emulates the way gas particles fill a vacuum. The robots expand from an initial compact state, based on a competition between attraction and repulsion behaviors that depend on distances to obstacles and other robots. We use a set of discrete ranges (Figure 4) to tune attraction and repulsion behaviors to maintain a medium-range distance from objects. These simple behaviors allow a robot swarm to expand from a tight grouping into a maximal dispersion that maintains nearest-neighbor communications (Figure 7).

A different model is used to search a space when there are not enough robots to completely fill it. The simplest of these "guided growth" methods uses the gas expansion model in conjunction with user-designated "barrier" robots, which emit barrier pheromones that prevent other robots from coming near. The user can designate one or more robots to perform such a role via remote tagging using a laser designator or a special topological command.

A more advanced form of guided growth is inspired by analogies to plant growth. One robot is designated as a "bud," and given a repulsive urge that is stronger than its attraction to other robots (Figure 5a). As it moves away from them, they expand to fill the space (Figure 5b) to maintain communications connectivity. The bud emits a growth inhibitor pheromone, which inhibits the formation of other buds, so that the robots tend to string out in a column that stretches away from the user. When a bud determines it

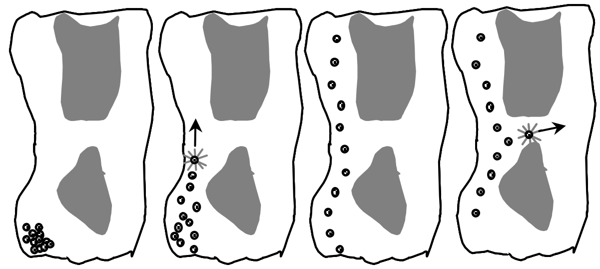

Figure 5: A "bud" acts as a single growth point until it hits a dead end, then a new "bud" takes over.

can make no more forward progress, it stops transmitting the growth inhibitor (Figure 5c). In the absence of growth inhibitor, other robots that detect open space can become buds (Figure 5d).

5.3 World Embedded Computation

Complex forms of world embedded computation are realized by combining robot motion with propagation of more than one virtual pheromone type. For example, using dual pheromone wavefronts, a robot swarm can discover and converge upon choke points (i.e. bottlenecks). This process has several steps as illustrated in Figure 6. In the first step, robots disperse evenly from the start (S) until they reach a target (T). The robot that sees T first propagates a pheromone. When the pheromone

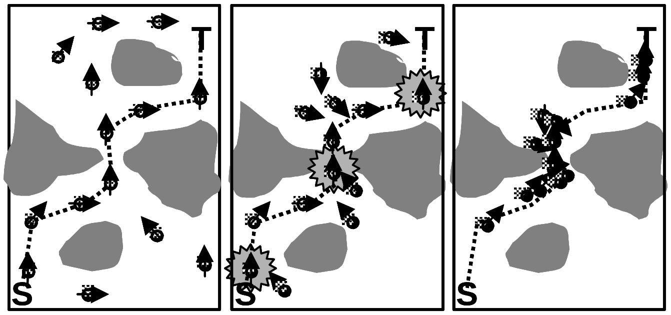

Figure 6: Robots locate a choke point by balancing the direction vectors of two opposing pheromone gradients.

wavefront reaches the robot closest to S, it initiates a different pheromone message that propagates back through the swarm in the opposite direction. Now, each robot has received two distinct pheromone messages, providing the direction vector of the local gradient toward S and T. The sum of these two vectors is the direction to the shortest path between S and T, the dotted line. When robots converge on this path, as shown in the center panel of Figure 6, the ones that that detect that they are in a narrow corridor emit a third pheromone that propagates only a short distance. This message attracts other robots so they clump at choke points, as the rightmost panel of Figure 6 illustrates.

5.4 World Embedded Display

Robots act as pixels in a world embedded display. The data each robot displays is a single character, encoded in a flashing barcode pattern that can be decoded by the head-mounted camera. This character encodes the direction of the local gradient vector that should be displayed to the user. The camera senses this data at a certain 2-D location in the image plane, and then the system places an icon representing the data at that location in the user's HMD, so it visually overlays the transmitting robot. Arrows appear to float above the robots, a visual indication of the diffusion gradient.

When the robot is conveying directional data, the user must share a common reference frame. A compass is often impractical, especially in indoor environments. Another way to establish a common reference frame is to design the beacons on each robot to transmit different messages in different directions (figure 8). These directional messages can be encoded such that the vector direction transmitted to the front of the robot is

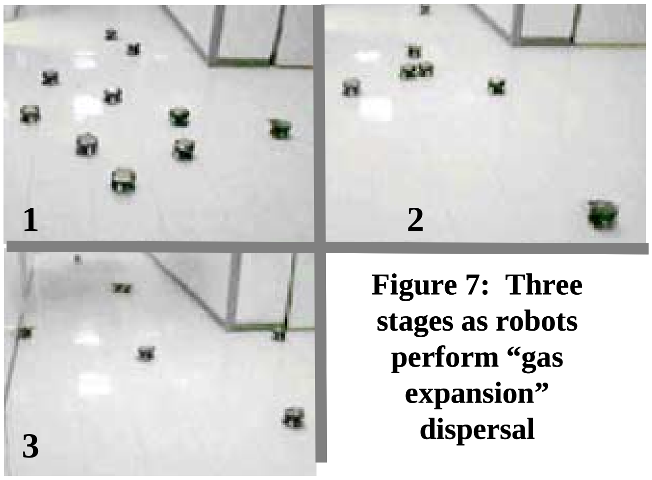

Figure 7: Three stages as robots perform "gas expansion" dispersal

180° from the vector transmitted to the rear. Likewise, the vector direction transmitted to side of the robot is 90° from the direction transmitted to the front. So from any viewing angle the decoded gradient vector will always appear to be pointing the same way relative to the physical world.

6. Recent Results

We have a swarm of 20 pherobots custom designed for us by Diversified Enterprises (Figure 8). The control system was originally written in Java, using the Teambots [18] environment which also allows us to simulate algorithms. Java on the PalmV robot controller, using a small virtual machine called WABA, proved too slow. By porting to C++ and making some other speedups we have reduced cycle time from 3 seconds to under 0.4 seconds.

We have demonstrated the gas expansion algorithm as shown in figure 7. We have also prototyped a transmitter mast for sending data to the user's head-mounted augmented reality display (figure 8). A camera with a bandpass filter can track the blinking transmitters fast enough to update the vector data on the user's display faster than once per second.

7. Related Work

Several related efforts in robotics have been driven by some of the same biological inspirations that lie behind our own work. In particular, Lewis and Bekey [13] have shown how a swarm of nanorobots might be organized

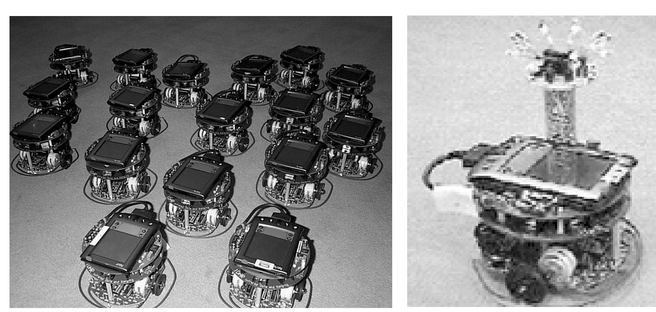

Figure 8: A robot swarm, and one robot with mast mounted for transmitting data to AR display.

using diffusion of distinct chemical markers to perform tasks such as removal of a tumor.

In Werger and Mataric [19], robots physically embody a pheromone trail by forming a contiguous chain. In our work, communication between robots indicates the pheromone trails. This gives our pherobots the advantage of more rapid dispersion of pheromone trails, and a much wider variety of pheromone types.

In the somewhat different domain of distributed sensor networks. Intanagonwiwat et al [11] use strictly local message-passing to find efficient paths for information flow within a network of distributed sensor nodes. McLurkin [14] uses a combination of pheromone messages that produce diffusion gradients and agent messages that hop from node to node in a directed fashion. Both Intanagonwiwat and McLurkin rely on explicit one-to-one communication between nodes, which requires that each node have a unique ID. They do not use their communications medium to sense the environment as we do.

8. Acknowledgements

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9. References

[1] Arkin, R.C. 1998. *Behavior-Based Robotics*. MIT Press, Cambridge, MA.

[2] Arkin, R.C. and Bekey, G.A. (editors). 1997. *Robot Colonies*. Kluwer Academic Publishers.

[3] Azuma, R., Hoff, B., Neely III, H., Sarfaty, R. 1999. A Motion-Stabilized Outdoor Augmented Reality System, *Proc. IEEE VR '99*, Houston, TX, pp. 252-259.

[4] Bonabeau, E., Dorigo, M., and Theraulaz, G., 1999. *Swarm Intelligence: From Natural to Artificial Systems.* New York, Oxford University Press.

[5] Deneubourg, J. and Goss, S. 1984. Collective Patterns and Decision-Making, *Ethology, Ecology, and Evolution*, 1:295-311.

[6] Dijkstra, E.W. 1959. A Note on Two Problems in Connection with Graph Theory, *Numerische Mathematik*, 1:269-271.

[7] Gage, D.W. 1992. Command and Control for Many-Robot Systems, In *Unmanned Systems Magazine*, 10(4):28-34.

[8] Gage, D.W. 1993. How to Communicate with Zillions of Robots, In *Proc. SPIE Mobile Robots VIII*, Boston, MA, 2058:250-257.

[9] Goss, S., Beckers, R., Deneubourg, J., Aron, S., and Pasteels, J. 1990. How Trail Laying and Trail Following Can Solve Foraging Problems, In *Behavioral Mechanisms of Food Selection*, ed. R. Hughes, Springer-Verlag, Heidelberg, Germany, pp. 661-678.

[10] Holland, O. and Melhuish, C. 2000. Stigmergy, self-organization, and sorting in collective robotics. *Artificial Life*, 5:2.

[11] Intanagonwiwat, C., Govindan, R., and Estrin, D. 2000. Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," In *Proc. 6th Annual Int. Conf. Mobile Computing and Networks (MobiCOM 2000)*, Boston, MA.

[12] JPL Sensor Webs: *http://sensorwebs.jpl.nasa.gov*.

[13] Lewis, M.A., and Bekey, G.A. 1992. The Behavioral Self-Organization of Nanorobots Using Local Rules," In *Proc. 1992 IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Raleigh, NC.

[14] McLurkin, J. 1999. Algorithms for distributed sensor networks, In Masters Thesis for Electrical Engineering U. California, Berkeley.

[15] Mitchell, J.S.B., Payton, D., and Keirsey, D. 1987. Planning and Reasoning for Autonomous Vehicle Control, *Int J. Intelligent Systems*, Vol. 2.

[16] Payton, D.W. 1990. Internalized Plans: A Representation for Action Resources, in *Designing Autonomous Agents*, ed. Pattie Maes, MIT Press, Cambridge, Mass, pp. 89-103.

[17] Ünsal, C. and Bay, J. 1994. Spatial Self-Organization in Large Populations of Mobile Robots," *IEEE Int. Symp. on Intelligent Control*, pp. 249-254.

[18] Web site: *http://www.teambots.org/*

[19] Werger, B.B., and Mataric, M.J. 1996. Robotic food chains: Externalization of state and program for minimal-agent foraging, In P*roc. 4th Int. Conf. Simulation of Adaptive Behavior: From Animals to Animats 4*, MIT Press, pp. 625-6