Digital Pheromone Mechanisms for Coordination of Unmanned Vehicles

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ABSTRACT
Many social insects coordinate without direct communication or complex reasoning. They deposit and sense chemicals ("pheromones") in a shared physical environment that participates actively in the system's dynamics, yielding robust adaptive coordination. Seeking such characteristics in engineered systems, we have developed a software environment that uses digital pheromones to coordinate computational agents. We apply digital pheromones to the control of air combat missions [8], developing several promising mechanisms for general agent coordination. This report describes pheromone-based movement control as a variety of potential-field-based methods, reviews the mechanisms we have developed, and describes their performance in several air combat scenarios.

Categories and Subject Descriptors
I.2.11 [**Artificial Intelligence**]: Distributed artificial intelligence - m*ultiagent systems*

General Terms: Algorithms, Experimentation.

Keywords
Fine-grained agents, stigmergy, pheromones, biomimetics

1. PHEROMONES ≈ POTENTIAL FIELDS
Pheromones are a particularly attractive way to construct a potential field that can guide coordinated physical movement. We use a potential field to guide unmanned robotic vehicles (URV's) through the battlespace. The vehicles climb a potential gradient centered on targets while avoiding gradients centered on threats. In warfighting, this field requires four characteristics not satisfied by existing approaches in robotics [12]. An architecture inspired by insect pheromones [7] satisfies these requirements

Diverse.—It must fuse information of various types and from various sources, including targets to be approached, threats to be avoided, and the presence of other URV's with whom coordination is required. Ants can respond to combinations of pheromones, reacting to multiple inputs at the same time.

Distributed.—Centralized processing of a potential field imposes bottlenecks and offers local vulnerabilities to attack. Pheromone deposits are stored throughout the environment (digitally, on unattended ground sensors), close to where they are generated, and are used primarily by ants that are near them.

Decentralized.—Efficiency and robustness require that system components be able to make local decisions without centralized control, ideally on the basis of nearest-neighbor interactions. Both ant behavior and pheromone field maintenance are decentralized. Ants interact only with the pheromones in their immediate vicinity. Because diffusion falls off rapidly with distance, deposits contribute to the field only in their immediate vicinity.

Dynamic.—The battlespace is uncertain and rapidly changing. The field must be able to incorporate changes rapidly. Under continuous reinforcement, pheromone strength stabilizes rapidly [2]. New information is quickly integrated into the field, while obsolete information is forgotten through evaporation.

A digital pheromone implementation has two components: *place agents* (which maintain the pheromone field and perform aggregation, evaporation, and diffusion), and *walkers* (which deposit and react to the field). Such techniques can play chess [4] and do combinatorial optimization [1], and we have applied them to manufacturing [2] and military C^2 [8].

2. BASIC MECHANISMS
Basic mechanisms useful in the engineering deployment of pheromone mechanisms include combinations of multiple pheromones, using history in movement decisions, and ghost agents.

The pheromone vocabulary can be multipled in two ways. First [9], different flavors may reflect different features of the environment (e.g., hostile or friendly entities), and thus have different *semantics*. Second, different flavors with the same semantics (e.g., all generated by the same feature) may differ in their evaporation or propagation rate or threshold, thus having different *dynamics*, supporting (for example) both long-range detection and short-range discrimination [3].

A walker's movement should balance several factors. A strong gradient enables deterministic hill climbing that the walker should exploit. However, a weak gradient may result from noise in the system, and not provide reliable guidance. A momentum based on recent movements enables walkers to handle both cases.

The walker associated with a single physical robot is its *avatar*. A physical entity has only one avatar, which travels at the same speed as the physical entity that it represents. One avatar

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may send out many unembodied walkers, or *ghosts*. Ghosts move as fast as the network among place agents can carry them. Because they are more numerous than physical entities and their associated avatars, they can do "what-if" explorations that physical entities could not afford, and generate emergent behavior [10] (e.g., path condensation) by their interactions. Because they move faster than physical entities and their avatars, they can look ahead to plan an avatar's next steps.

3. OPERATIONAL SCENARIOS

We have demonstrated these mechanisms in four increasingly sophisticated military scenarios. In *SEADy Storm* [5], friendly (Blue) forces defend a region of a hex grid against invading Red forces, including ground troops and air defense units that protect the ground troops from Blue attack. Blue has bombers to attack ground troops and fighters to suppress enemy air defenses. [6] discusses the performance of digital pheromones in such a system. *CyberStorm* expands the range of unit types to include enemy armored and infantry battalions, air defense units, distinct headquarters types for regiments, air defense, and the entire corps, and fueling stations, and five types of friendly aircrafts. The environment includes bridges and road crossings (which speed the movement of ground units that encounter them) and oil fields (which Red seeks to attack and Blue seeks to protect). Combat outcome is based on the percentage survival of the oil fields. Experiments with this environment demonstrate the need for ghost agents to sample the primary pheromone field at a statistically more significant level, and preprocess it for use by Blue avatars and the physical resources with which they are associated. *Super Cyber Storm* includes a significantly wider range of entity types, combat resolution on the basis of individual weapon type rather than unit type, more realistic dependencies among entities (for example, the effectiveness of Red air defense now depends on the status of other Red air defense units), and a "pop-up" Red capability that lets us increase greatly the range of changes in Red's visibility as a scenario unfolds. This environment permits us to assess the effectiveness of ghost-based pheromones in dealing with pop-up threats, and is the basis for our work on evolving ghost agents [13]. Recently, these algorithms have been applied successfully to an experiment by the *US Joint Forces Command* on the effectiveness of swarming UAV's (unmanned air vehicles) in suppressing antiaircraft threats [11], showing significant performance improvements over the baseline.

A full version of this paper is available at http://www.erim.org/~vparunak/AAMAS02ADAPTIV.pdf .

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