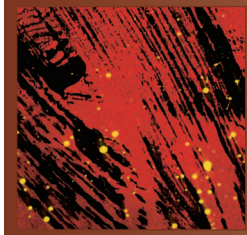# Swarms and Swarm Intelligence

Michael G. Hinchey, Loyola College in Maryland
Roy Sterritt, University of Ulster
Chris Rouff, Lockheed Martin Advanced Technology Laboratories

Intelligent swarm technologies solve complex problems that traditional approaches cannot.

We are all familiar with swarms in nature. The word *swarm* conjures up images of large groups of small insects in which each member performs a simple role, but the action produces complex behavior as a whole. The emergence of such complex behavior extends beyond swarms. Similar complex social structures also occur in higher-order animals and insects that don't swarm: colonies of ants, flocks of birds, or packs of wolves.

These groups behave like swarms in many ways. Wolves, for example, accept the alpha male and female as leaders that communicate with the pack via body language and facial expressions. The alpha male marks his pack's territory and excludes wolves that are not members.

Several areas of computer science have adopted the idea that swarms can solve complex problems. For our purposes, the term swarm refers to a large group of simple components working together to achieve a goal and produce significant results. Swarms may operate on or under the Earth's surface, under water, or on other planets.

SWARMS AND INTELLIGENCE

Swarms consist of many simple entities that have local interactions, including interacting with the environment. The emergence of complex, or macroscopic, behaviors and the ability to achieve significant results as a team result from combining simple, or microscopic, behaviors.

Intelligent swarms

Intelligent swarm technology is based on aggregates of individual swarm members that also exhibit independent intelligence. Members of the intelligent swarm can be heterogeneous or homogeneous. Due to their differing environments, members can become a heterogeneous swarm as they learn different tasks and develop different goals, even if they begin as homogeneous. Intelligent swarms can also comprise heterogeneous elements from the outset, reflecting different capabilities as well as a possible social structure.

Researchers have used agent swarms as a computer modeling technique and as a tool to study complex systems. Simulation examples include bird swarms and business, economics, and ecological systems. In swarm simulations, each agent tries to maximize its given parameters.

In terms of bird swarms, each bird tries to find another to fly with, and then flies slightly higher to one side to reduce drag, with the birds eventually forming a flock. Other types of swarm simulations exhibit unlikely emergent behaviors, which are sums of simple individual behaviors that form complex and often unexpected behaviors when aggregated.

Swarm intelligence

Gerardo Beni and Jing Wang introduced the term *swarm intelligence* in a 1989 article ("Swarm Intelligence," *Proc. 7th Ann. Meeting of the Robotics Society of Japan*, RSJ Press, 1989, pp. 425-428). Swarm intelligence techniques (note the difference from *intelligent swarms*) are population-based stochastic methods used in combinatorial optimization problems in which the collective behavior of relatively simple individuals arises from their local interactions with their environment to produce functional global patterns. Swarm intelligence represents a metaheuristic approach to solving a variety of problems.

Swarm robotics refers to the application of swarm intelligence techniques to the analysis of activities in which the agents are physical robotic devices that can effect changes in their environments based on intelligent decision-making from various input. The robots can walk, move on wheels, or operate under water or on other planets.

SWARMS APPLICATIONS

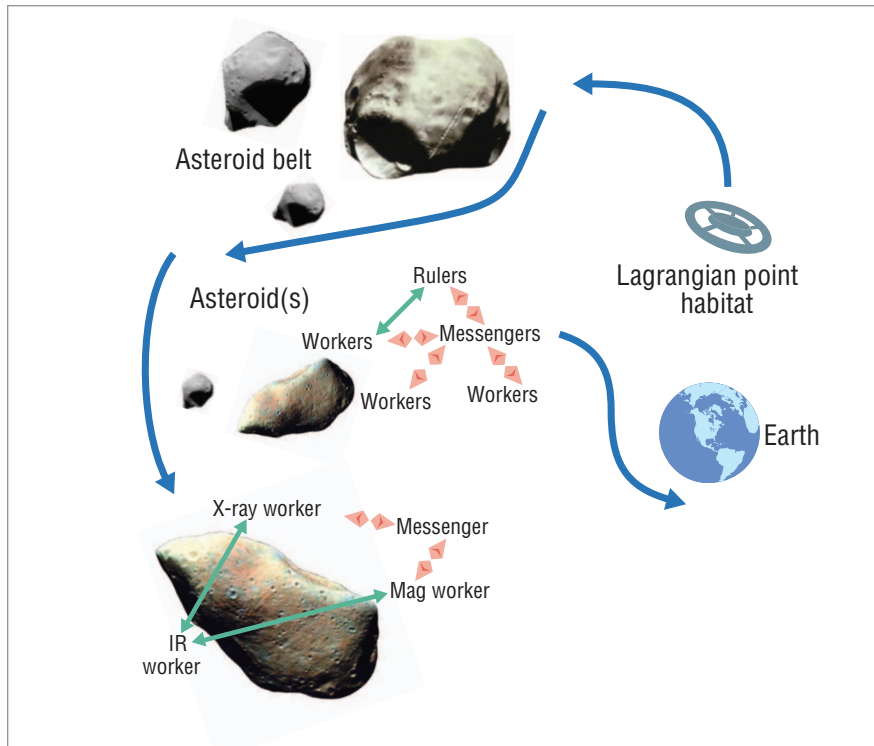Practitioners in fields such as telephone switching, network routing,

Figure 1. Prospecting asteroid mission overview. A transport ship launched from Earth travels to a point in space where gravitational forces on small objects are all but negligible. From the Lagrangian point, 1,000 spacecraft will be launched into the asteroid belt, forming subswarms under the control of a leader or ruler. The subswarms will collect data on asteroids of interest, relaying it back to rulers, which ultimately send it back to Earth.

data categorizing, and shortest-path optimizations—among others—are investigating swarm behavior for potential use in applications.

BioTracking

As part of the BioTracking project at the Georgia Institute of Technology, researchers have been studying the behavior of bees (T. Balch et al., "How A.I. and Multi-Robot Systems Research Will Accelerate Our Understanding of Social Animal Behavior," *Proc. IEEE*, July 2006, pp. 1445-1463).

To expedite the understanding of how large-scale robust behavior emerges from the simple behavior of individuals, the project videotaped bees' behavior over time, using a computer vision system to analyze data on the insects' sequential movements to encode the location of food supplies. The intention was to use bees' behavior models to improve simple robot teams capable of complex operations.

Eliminating the need for robots to have a priori knowledge of the environment or direct communication with each other is key to this model.

Particle swarm optimization

PSO is a global optimization algorithm for dealing with problems in which a point or surface in an *n*-dimensional space best represents a solution. Potential solutions are plotted in this space and seeded with an initial velocity. Particles move through the solution space, and certain fitness criteria evaluate them. Over time, particles accelerate toward those with better fitness values.

Penn State University researchers have focused on particle swarms for the development of *quantitative structure activity relationships* models used in drug design (W. Cedeño and D.K. Agrafiotis, "Combining Particle Swarms and *k*-Nearest Neighbors for the Development of Quantitative Structure-Activity Relationships," *Biocomputing*, 2003,

pp. 43-53). The models applied artificial neural networks, *k*-nearest neighbor, and kernel regression techniques. Binary and niching particle swarms solved feature selection and feature weighting problems.

Particle swarms also have influenced the computer animation field. Rather than scripting the path of each individual bird in a flock, Craig W. Reynolds' Boids project as described in "Flocks, Herds, and Schools: A Distributed Behavioral Model" (*Proc. 14th Ann. Conf. Computer Graphics and Interactive Techniques*, ACM Press, 1987, pp. 25-34) elaborates on a particle swarm using simulated birds as the particles. The simulated flock's aggregate motion behaves much as a real flock would in nature—the dense interaction comprises the relatively simple behaviors of each of the simulated birds choosing its own path.

Ant colony optimization

Eric Bonabeau, Marco Dorigo, and Guy Theraulaz reported much success with their pioneer efforts using social behavior patterns of ant colonies to model difficult combinational optimization problems in *Swarm Intelligence: From Natural to Artificial Systems* (Oxford Univ. Press, 1999). In their work, artificial ants travel through a problem graph depositing artificial or digital pheromones to enable other ants to determine more optimal solutions. Ant colony optimization has solved the traveling salesman problem, which investigates the shortest route to several cities and the subsequent return to a starting point, as well as network and Internet optimizations.

Unmanned underwater vehicles

University of California, Berkeley, researchers are studying networks of unmanned underwater vehicles. Each UUV relies on the same template information containing plans, subplans, and its own local situation map to make independent decisions. The UUVs, however, cooperate in the network to conduct, for example, group pursuit strategy experiments in a shallow water pool. They can identify ves-

sels of interest and pursue them in environments in which a larger underwater vessel would be destroyed.

Swarmcasting

A technique that exploits the acceleration of distributed downloading to provide high-resolution video, audio, and peer-to-peer data streams, swarmcasting also significantly reduces needed bandwidth. ACTLab's Alluvium project at the University of Texas at Austin powers ACTLab TV (http://actlab.tv), a concept personal TV station, using peer-to-peer media streaming software. Essentially, it applies the swarm analogy to break down video files into small pieces so that the system can download components from several machines simultaneously. Thus, the user can start watching the video before the download completes.

Swarmcast (www.swarmcast.com), a commercial company, supports delivery of large amounts of data over networks using similar concepts and strives to be a significant contributor to the next generation of Internet TV.

Paintable computers

Closely related to the swarm idea is the concept of a paintable computer, as Bill Butera proposed in his PhD dissertation ("Programming a Paintable Computer," doctoral dissertation, MIT Media Laboratory, MIT, 2002).

The idea is that several thousand parasitically powered and pinless integrated circuits—each the size of a match head—with an onboard microprocessor, small memory, and wireless connectivity can be suspended in a viscous material and then "painted" on various surfaces. Once exposed to a power source, the components or pfrags self-organize and communicate with external systems via physical contact with objects fitted with a transceiver that defines a suitable communication protocol.

NASA's use of swarms

NASA has been investigating swarms for future space exploration missions. The three submissions in the autonomous nanotechnology swarm (ANTS) concept mission deploy multiple spacecraft to provide backups and ensure survival in space.

In one incarnation, a Saturn autonomous ring array will launch 1,000 picoclass spacecraft with specialized instruments—organized as 10 subswarms—to perform in situ exploration of Saturn's rings to understand their constitution and formation.

The *lander amorphous rover antenna* ANTS application is a lunar-base-activities submission that exploits new NASA-developed technologies in the miniaturized robotics field. Forming the basis for launching landers to the moon from remote sites, LARA also uses innovative techniques to move rovers in an amoeboid-like fashion over the moon's uneven terrain.

The prospecting asteroid mission involves launching a swarm of autonomous picoclass spacecraft (approximately 1 kilogram) to explore the asteroid belt for asteroids with certain characteristics. Figure 1 provides an overview of the PAM mission concept. In this submission, a transport ship launched from Earth will travel to a point in space where gravitational forces on small objects, such as picoclass spacecraft, are all but negligible. Assembled en route from Earth, 1,000 spacecraft will be launched from the Lagrangian point into the asteroid belt. The spacecraft—equipped with specialized instruments—will form subswarms to collect relevant data from asteroids of interest.

Given that many of the spacecraft could collide with one another or with asteroids and become lost, multiple-spacecraft missions offer greater likelihood of survival and flexibility than single-spacecraft missions. Additionally, the self-directed swarm will exhibit intelligence, which is critical since round-trip delays in communication from Earth can stretch upward of 40 minutes. The mission could be lost before ground control is notified of a problem.

Nature-inspired intelligent swarm technology deals with complex problems that might be impossible to solve using traditional technologies and approaches. This field has spawned a highly successful conference series, the IEEE Swarm Intelligence Symposium, the fourth edition of which takes place this April in Hawaii. This technology has even infiltrated pop culture and is the subject of Michael Crichton's science fiction novel, *Prey*. ■

Michael G. Hinchey is a professor of computer science at Loyola College in Maryland. Contact him at mhinchey@loyola.edu.

Roy Sterritt is an academic and researcher in the Computer Science Research Institute at the University of Ulster. Contact him at r.sterritt@ulster.ac.uk.

Chris Rouff is manager, Technology and Business Development, at Lockheed Martin Advanced Technology Laboratories. Contact him at crouff@atl.lmco.com.