Swarming: From Simple Models to Promising New Robotics Applications

SIAM NEWS volume 42/Number 9
November 2009, page 1,4
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On seeing a flock of birds or a school of fish, most people briefly acknowledge the wonders of nature, then move on. Few focus on an individual goose or herring, or wonder for more than a moment how its interacting with its neighbors, or how the individuals are coordinating their movements to stay together.

That can be left to Andrea Bertozzi.

Bertozzi, the director of applied mathematics at the University of California, Los Angeles, gave the SIAM/AWM Sonia Kovalevsky Lecture at this year’s SIAM Annual Meeting on one of her current interests: swarming. In the talk, titled “Swarming by Nature and by Design,” Bertozzi covered efforts to introduce concepts of physics into mathematical biology models, develop and improve on continuous and discrete models of swarming, and advance potential applications of the work.

“First Principles” of Swarming

The basic properties of biological aggregations tend to be fairly simple, Bertozzi points out. A group executes a large-scale, coordinated movement, but without centralized control; the density of the group remains fairly constant toward the center and has a sharp edge at the aggregation’s periphery; and the distance over which individuals can interact tends to be much smaller that the group’s overall size. These properties allow for simple models under assumptions, like a conserved population and a velocity vector dependent on local population gradients.

Bertozzi and her colleagues are working to extend these simple models.

“If we see this in nature, we have to find models that have that behavior,” she says. “But rather than using [global] behavior to construct the model, we want to think about constructing a model based on local interactions, and then see [if] that model yields the global behavior we’re expecting.”

Bertozzi and postdoc Chad Topaz demonstrated this approach in a 2004 paper in SIAM Journal on Applied Mathematics, modeling the propagation of constant-density groups in two dimensions. Although the model is limited in the kinds of behavior it can simulate, as Bertozzi explained in her talk, it does result in interesting patterns, such as rotation—similar to vortex motion for two-dimensional fluids. Moreover, the analogy between aggregation and fluids has led to some new mathematics. Recently, for example, Bertozzi and collaborators Thomas Laurent and José Carrillo, as described this year in Nonlinearity, proved a sharp condition on the shape of the interaction kernel such that the basic aggregation model blows up in finite time.

From there, she moved on to new models, trying, as she puts it, to “think like a physicist” and identify “first principles” of swarming: for example, that the population of individuals in a swarm would sense the “average” density of the nearby population. Being biologically sensed, this average would decay over distance. In addition, because social attraction is the main precursor of swarming, members of the group would tend to climb population gradients—that is, move toward the areas where more...
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individuals are gathered. This collection of “first principles” related to social attention is what Bertinucci needs to predict velocity in the new model.

Along with attention, the models need a mechanism for dispersal. If overcrowding occurred without such a mechanism, the model would essentially be trying to place multiple individuals in the same physical space. Hence the first principles of dispersal: If members of the group get too close to each other, they should disperse a distance proportional to the square of the distance between each other, which is a result that also holds in two dimensions and reflects the swarms of locusts and schools of fish seen in nature. (The work appeared in the Bulletin of Mathemat-

ics Biology in 2006.)

Such models could be important step toward harnessing the power of swarms for real-world applications in myriad fields. The applications in sensor networks alone are numerous, as artificial platforms can overcome some of the theoretical limitations of natural swarms. Take, for example, a school of fish.

“Unless there’s some secret ESP we don’t know about,” Bertinucci says, “fish probably don’t communicate over very large distances. But that doesn’t mean that you couldn’t accomplish that with an artificial autonomous robot, or another form of communication.”

A swarm of robots, then, might be used for remote sensing, with individual robots transmitting the information both to each other and to, in a distant observe. Having multiple individuals take readings in the same area builds redundancy, improving accuracy even if some of the data is noisy, and the swarm, whatever its measuring, could be sent into environments too dangerous for human beings.

“You might immediately think of defense,” Bertinucci says, noting that the group is currently studying applications that involve searching for targets, including land mines. “But you think of forest fires and so on, and there are so many basic problems that are very important for humanity.”

Order in Chaos

To develop practical algorithms for real-world use, Bertinucci and her colleagues began developing discrete models that would track individual particles in a swarm. The velocity of a particle in a swarm, Bertinucci explains, changes in response to multiple forces exerted on the particle by other particles in the swarm, and the preporation of the environment, which changes the shape of the shape of the swarm, and the swarm, whatever its measuring, could be sent into environments too dangerous for human beings.

The same issue arises in continuous fields of interacting molecules, she continued, describing work published in Physica D (2007). “For example, we do not describe the continuous field in term of Lennard-Jones interactions between molecules.”

Follow the Yellow Brick—or the Blue Tape—Road

Even with discrete models that more accurately capture real-world behavior, technical challenges must be addressed. For instance, before such systems can be implemented, longevity is an issue for devices being sent into hostile environments, as are energy consumption and reliable communications. Bertinucci has been involved with robotics experiments for the last five years, with the goal of testing various sensing and cooperative motion algorithms on laboratory testbeds. Her interest dates back to 2004, when she worked on a project involving Nekton Research (now part of Roberts) studying environmental boundary tracking. Soon after, Richard Murray of Caltech invited her to bring some UCLA students to his Multi-Vehicle Wireless Testbed to test algorithms.

“I found a club at UCLA where the students were building robots for a competition,” Bertinucci remembers, “I put three outstanding students: Chung Hoese, Biao Nguyen, and David Yang.”

The students took advantage of Murray’s offer, and eventually became co-authors (with Murray, Bertinucci, then-PhD student Zhipu Jin, and then-postdoc Daniel Man- thaler) of two American Control Conference papers on a testbed implementation of robots following an environmental boundary and an implementation of the Morse potential pairwise interaction model on a vehicle called the Kelley, which rolls on casters and uses model airplane fans for propulsion. Afterward, Hoese decided to stay at UCLA in a master’s degree program in engineering, with other students, he ended up designing robots for a testbed that Bertinucci and engineering colleagues Emilio Frazzoli developed in the Applied Math Lab at UCLA.

The faculty researcher-undergrad collaboration has continued ever since; students in mathematics and engineering alike have contributed to the implementation of Bertinucci’s algorithms.

“They come up with ideas and think that it’s so much fun, and they can’t believe someone’s going to pay them to do this,” Bertinucci says, recalling that electrical engineering undergraduate Kevin Leung designed a robot car from scratch with a $20 sensor after realizing he could improve on the first-generation testbed they had used. Of course, with new hardware, new algorithms were needed to govern their movement. One Vlad Voroninov, another undergraduate—this time in mathematics—who implemented a differential equation steering-control model, developed at the Naval Research Lab, on the testbed.

The UCLA testbed has since been used for many new projects, including a joint effort of UCLA and the Institute for Pure and Applied Mathematics on environmental mapping by robots with finned sensor fins, as well as a biometric boundary-tracking project undertaken by Trevor Ashley, a Harvey Mudd undergraduate. Ashley, with Bertinucci and UCLA electrical engineering graduate student Abhijit Joshi and Rick Haug, implemented an algorithm in a vehicle that tracks a boundary separating two regions based only on local sensor information, even with a low signal-to-noise ratio.

Using an on-board analog-to-digital converter, they apply a cumulative time filter to the sensor data to determine whether a vehicle had crossed the boundary; the filtered data was then output to a steering con-

The algorithm and the motion of the robots call it mind as that following a planet’s surface or the ground. Cooperative sensing algorithms are already in use. Bertinucci mentions Naomi Leonard, an engineering professor at Princeton who has used small robotic fish to monitor algae blooms in Monterey Bay, California (see “Control-Theoretic Chaos: New Waters for Synchronous Swimmers,” SIAM News, November 2005). Bertinucci and colleagues have extended the robot boundary-tracking algorithm, implementing it to find edges in high-dimensional hyperspec-

tral imagery, she is currently working with researchers at Lawrence Berkeley National Laboratory to use these algorithms to control an atomic force microscope.

Other algorithms designed to locate individual targets, are being implemented. “In looking at some of these applications in searching for targets, we’re looking at how efficiently one would have to have a team—a small team composed of swarms, is there an optimal swarm size?” Bertinucci says. “We’ve found that there is—you actually do better with a small group working together than using the same resources and sending them out as individuals.”

In other words, it’s all about teamwork—whether you’re a researcher or a robot.

Michelle Spiegel is a contributing editor at SIAM News.