

# Naomi Ehrich Leonard's School of Collaboration

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In the fall of 2004, Princeton University professor of mechanical and aerospace engineering Naomi Ehrich Leonard won a MacArthur Fellowship. Popularly named a “genius grant,” the award recognizes her work in control theory and its applications to autonomous underwater vehicles. Leonard’s talent lies in creatively exploring solutions to control problems through combining diverse expertise in such areas as mechanics, mathematics, computer science, and robotics with an interest in biology, oceanography, and ecology. Most recently, she has been organizing groups of robotic underwater vehicles to create an adaptive sensor network. Leonard’s work, characterized by an aptitude to delve into areas of study apart from her own engineering expertise, reflects her ability to collaborate with scientists from other fields, explore complex problems, and do sophisticated work that offers remarkable potential for applications outside its immediate arena.

## Geometric control

Leonard showed an early aptitude to cross-pollinate her ideas with different approaches while she was working on her PhD, which she received in 1994 at the University of Maryland, College Park. Under the direction of P.S. Krishnaprasad, Leonard was working on geometric control, particularly in underactuated robotic systems with restricted freedom of motion. Thinking about problems like controlling spacecraft orientation, Leonard developed theory that would help her systematically control motion in underactuated vehicles, a problem similar to parallel-parking a car. Making use of periodic control signals, averaging theory, and the geometry of (not necessarily linear) configuration spaces to predict how motion sequences in actuated directions would lead to motion in unactuated directions, she developed an algorithm for generating motions in any direction.

Leonard asked Maryland professor David Akin if she could try her control algorithm by testing a vehicle in his Space Systems lab, a large neutral-buoyancy tank, in an

experiment that contributed to her interest in the control of underwater vehicles. At Princeton, she began thinking about mechanics of bodies in water and considering ways to stabilize them. She based her approach on natural control forces such as gravity and used tools from geometric mechanics to determine the conditions for using these control forces to stabilize the vehicle’s motion.

“The idea was to think about using controls that could be realized by mechanical means so that the controlled system would still look like a mechanical system,” Leonard says. “The objective then was to choose among such controllers so that the controlled mechanical system was provably stable.”

Around this time, Leonard met Jerry Marsden, now Carl F. Braun Professor of Engineering and Control of Dynamical Systems at the California Institute of Technology. Together with Anthony Bloch, professor of mathematics at the University of Michigan, they began collaborating on geometric control of mechanical systems.

“The geometric point of view can be a very useful supplement to traditional techniques of asymptotics and control theory,” Marsden says. “She had already made a lot of use of this, but there were many more things that she could do.” Leonard’s interdisciplinary interests facilitated the joint effort. “She took the trouble to learn the mathematics properly,” Marsden says, “and this good mathematical infrastructure has been really important in her career.”

By 1997, the team began developing theory for controlling larger classes of mechanical systems using feedback laws that allow the control system to be described as a mechanical system itself. The goal was to apply control but keep the system “Lagrangian or Hamiltonian,” as Bloch explains, “so that it behaves like a mechanical system without forces.” Such systems have symmetry properties associated with them and, as a consequence, conserved quantities over time. You can use these conserved quantities to build a Lyapunov function to prove the system’s stability. “We were able to change the energy of the system by putting in some feedback or forcing,” Bloch says, “so that the system remained Hamiltonian. The idea is to choose the control so that you match the

## Useful URLs

**Naomi Ehrich Leonard's home page:** [www.princeton.edu/~naomi](http://www.princeton.edu/~naomi)  
**Autonomous Ocean Sampling Network II:** [www.princeton.edu/~dcs/aoasn](http://www.princeton.edu/~dcs/aoasn)  
**Center for Autonomous Underwater Vehicle Research:** [www.cs.nps.navy.mil/auv](http://www.cs.nps.navy.mil/auv)  
**Geometry and Motion Control tutorial:** [www.math.princeton.edu/matalive/Geometry/index.html](http://www.math.princeton.edu/matalive/Geometry/index.html)

original system to your control system to keep it in this Lagrangian form.”

The team developed a general theory that it applied to various examples, and Leonard considered subtle ways of actuating systems as she studied bodies in the water. “I thought about the notion of controlling them by moving mass around inside, redistributing it inside the body,” she says. “How mass is distributed influences stability.” For example, something top-heavy dropped in the water will tip over, but something bottom-heavy will keep its orientation.

Leonard started working with buoyancy-driven underwater gliders to explore the possibilities of moving internal mass around to control orientation and motion. “You can change a glider’s mass or volume so that it either wants to go up or down and you can redistribute its mass to change its direction. In this way you can control its path,” she says.

### Multivehicle control

Moving from control of a single object, Leonard next considered multivehicle systems and decentralized strategies for controlling both a group’s shape and its overall dynamics. Leonard used the idea of artificial potentials, an obstacle-avoidance tool borrowed from the robotics community. A robot can sense an artificial potential field in its path as repulsive and stay clear of it.

In one project from 2001, Leonard and her students imposed artificial potentials—realized by the control forces on the vehicles—that behave like springs between underwater gliders. For example, the gliders can measure how close they are to each other, and when they come too close together, their actuators turn on and they push themselves away. When the gliders are too far away from each other, the actuators turn on to pull them closer together. Using artificial potentials to realize these forces makes it possible to analyze the group dynamics for stability and robustness.

Using this idea, Leonard’s team designed

glider formations by imposing appropriate spring lengths and constants that shape the group and individual glider dynamics and by introducing virtual bodies—moving “vehicles” that are only simulated on a computer. Artificial potentials imposed between vehicles and virtual bodies not only keep the vehicles in formation automatically but also let the formation move around and change shape according to changing virtual-body dynamics. These dynamics, implemented on a computer, are automated and designed using feedback to keep the group stably together and to enable desired translation, rotation, and expansion of its formation.

Leonard’s control algorithms can also enable glider missions for collecting data from the environment. In a sophisticated feedback loop, the gliders can send collected environmental data to the computer, which can then use the data to compute a new direction for the virtual-body dynamics and so for the glider group. For example, the gliders can estimate environmental gradients and move toward higher or lower values of various fields such as temperature, salinity, or phytoplankton concentration. With information pooling and path-shaping capabilities, Leonard’s controlled multivehicle group makes an excellent sensor network.

### “Schooling” sensor networks

The idea of creating sensor networks with robotic groups has a lot in common with the biological phenomena of animal aggregation, such as flocks of birds or schools of fish. Leonard credits her ideas in great measure to bioinspiration. “One of the things that animal aggregations do very well is forage for food, and we are foraging for information,” Leonard says. “We wouldn’t necessarily be trying to develop models that contain every last detail in the dynamics of these groups, but use them to predict some of the coarser behavior.”



Naomi Ehrich Leonard

A single fish might find food, but the food source might also be small, whereas a school of fish can find a much larger supply of food by communicating with each other about their environment. Leonard wants her underwater robotic sensor network to sample an environment in the same efficient way, taking advantage of data it finds collectively to locate rich data fields and move even faster on currents the network senses.

“The idea is to develop an adaptive, sustainable, and portable ocean observing and prediction system,” she says. “The data gets collected from all the vehicles and assimilated into ocean forecasting models that try in real time to estimate various kinds of signals and feed them back into the algorithms that determine where the vehicles should go to collect data.” The individual vehicles respond to what they measure, what their neighbors tell them, and what the ocean models predict.

In August 2003, Leonard tested her bio-inspired control theory in a month-long collaborative experiment dubbed Autonomous Ocean Sampling Network II (AOSN II). Working with a team of oceanographers, ecologists, engineers, mathematicians, and computer scientists in Monterey Bay, California, Leonard used a group of three underwater gliders that were among a dozen or so collaborating to collect oceanographic data, including water temperature, salinity, and phytoplankton concentration. The experiment tested the gliders as a coordinated group that moved together to gather data.

“In the second couple of weeks we had some success with actually getting the whole data stream moving, doing real-time predictions,” says Steve Ramp, research professor at the Naval Postgraduate School and one of the AOSN II collaborators.

Ramp and Leonard are heading up another multiuniversity research effort, Adaptive

Sampling and Prediction, scheduled to hit the water in August 2006. ASAP will expand the experiment with additional gliders and more sophisticated control theory as well as explore upwelling phenomena in Monterey Bay. Leonard is working on designing coordinated patterns and new kinds of feedback control for the glider fleet. The gliders should be able to move autonomously and optimize the data they collect in fields that change in space and time and in the presence of strong currents and other oceanic uncertainties.

Among other things, she is working with colleagues to come up with a good metric for adaptive sampling performance and to develop control laws that produce coordinated circular paths for vehicle groups. Ramp is looking forward to further collaboration on the project. "We thought we'd only just begun, just kind of stuck our big toe in the water," he says. "We really want to continue working on these things."

Leonard wants to think about creating sensor networks for collecting data at dif-

ferent scales, employing different kinds of patterns and coordination for adapting to the changing environment and using resources optimally. Synoptic views together with localized views could further many scientific goals of understanding complex dynamics where data is limited. For example, Leonard says there is interest in putting clusters of satellites in space to locate planets and stars as well as seismic sensors in the ocean to detect earthquakes. "There are lots of communities of people who think about adaptive sampling," she says, "where you're searching for something and you want to be smart about how you use your resources and be able to change your path."

Leonard's collaborative skills allow her to develop solutions by working with experts in other areas and drawing on new perspectives. She sees the advantages of finding the ways different people can best complement each other. Russ Davis, a re-

search oceanographer at the Scripps Institution of Oceanography who is working with her on AOSN II and ASAP, describes Leonard's collaborative talent. "She came to see some of the ways that we had used to measure how well an observing system was performing and has blended those with ideas she had from control theory and is starting to make whole areas of study."

Simon Levin, George M. Moffett Professor of Biology at Princeton, says that a lot of collaborative work, especially at the interface between biology and physics and mathematics, is happening now, particularly at Princeton. "As we look at large-scale problems and complex systems, nobody's got the expertise that's needed to address these problems," he says. Dealing with problems that occur on different scales of time and space and organizational complexity inspire collaborative efforts to pool expertise—not unlike the collective phenomenon of fish schools and Leonard's sensor networks—to discover the best solutions. ■

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