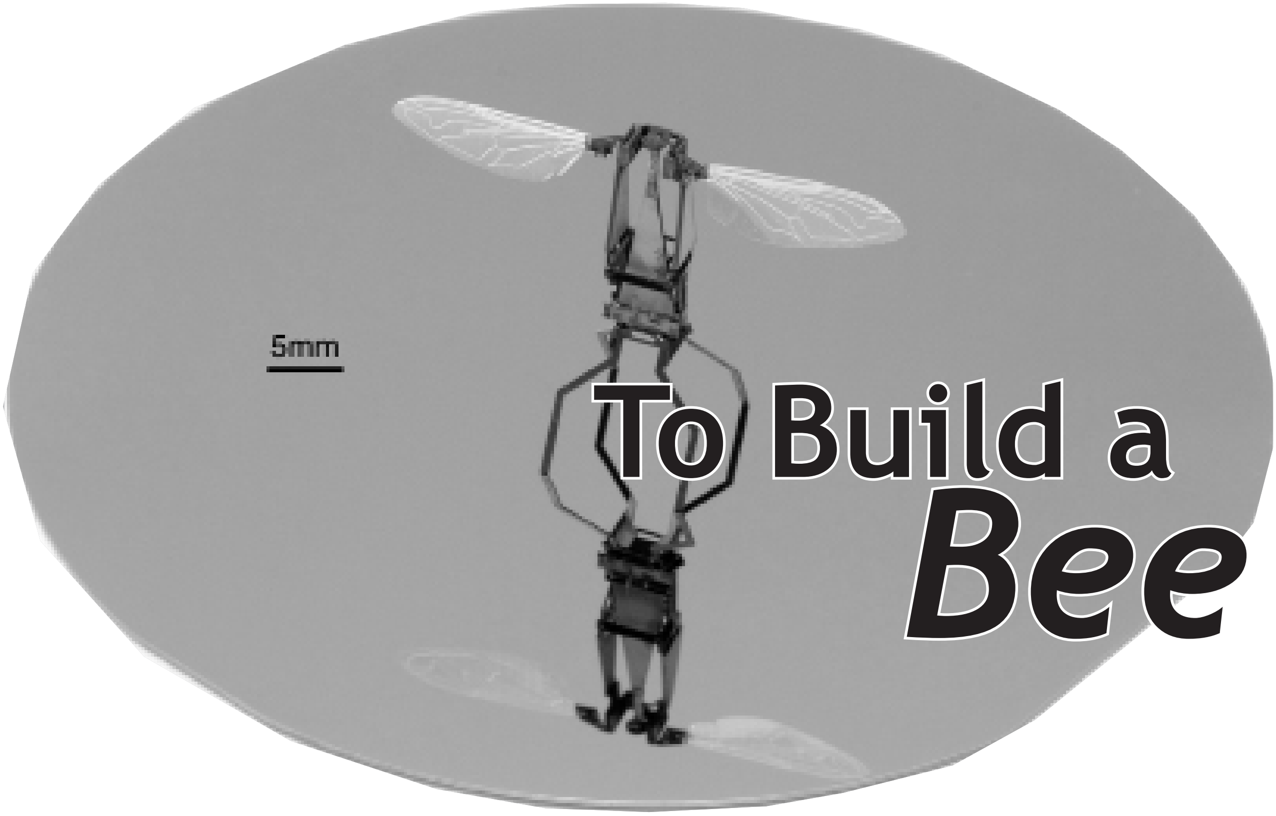

To Build a Bee

The Robobees project and the creation of a miniature, robotic pollinator

By Emily Howell

In our modern world of mass agriculture and industry where we have the security of plentiful food, we still rely on something as small and natural as the honey bee to help produce over 75 percent of crops worldwide (1). About one third of our diet comes from plants dependent on insect pollination, 80 percent of which relies on the honey bee (2). In England alone, bees do work that would require 30 million people if crops had to be pollinated by hand, and in the United States bees contribute close to 15 billion dollars to the value of crop production (2, 3).

Unfortunately, the honey bee populations are plummeting due to what researchers have named Colony Collapse Disorder (CCD). Since fall of 2007, massive numbers of honey bees have been dying off, and since then 36 percent of the 2.4 million hives in the U.S. have disappeared (4). The cause of these drastic declines in bee populations remains unknown.

A group of researchers at Harvard, however, are currently working on potential substitutes for the disappearing bees: robobees, or small, agile flying robots equipped with communication skills and pollen collecting abilities that imitate those of bees. The idea of robobees began when one of the researchers, Gu-Yeon Wei, a professor of Electrical Engineering at the Harvard School of Engineering and Applied Sciences (SEAS) watched the documentary "Silence of the Bees," which describes effects of CCD. Wei approached colleague Robert Wood, an associate professor of Electrical Engineering at SEAS and posed the question: what if we can find a technological solution to CCD? Thus began the Robobees project – a project incorporateing research from multiple disciplines while expanding engineering science into new realms. Here is a look at what is making these robobees buzz.

credit: courtesy of Rob Wood

The Disciplinary Diversity of the Team

The aspect of the Robobees project that members of the team emphasize as particularly exciting is the interdisciplinary nature of the research and the diverse group of people of different expertise that has come together. The Robobees team includes professors, postdoctoral, graduate students, and undergraduate students from multiple departments across Harvard's campus. Both Wood and Wei work in Electrical Engineering with SEAS, and they are joined by professors from the Computer Science, Applied Math, Materials Science, and Organismic & Evolutionary Biology departments, as well as by Joseph Ayers, a professor from the Department of Biology and Marine Science Center at Northeastern University. Additionally, thirteen postdoctoral researchers, nineteen graduate students, and sixteen undergraduates are currently assisting on some aspect of the robobees' creation (5).

Spring Berman, one of the postdoctoral researchers with a mechanical engineering background, says she loves the interdisciplinary aspect of the project, and the range of expertise and advice available (6). These interactions offer learning experiences for the professors as well. Wood describes this research program as an effective model for how to attack a complex, multi-disciplinary problem. Drawing expertise from multiple fields provides insights into how different disciplines attack the same problem. Of the whole project, Wood notes the "interaction that develops between people in traditionally separate fields when they work together" as being one of the most "interesting and rewarding" aspects. He credits Harvard's departmental structure with making such collaboration possible. "At Harvard [interdisciplinary work] is facilitated. There is no department structure which would frame a project like this into one discipline. So we're allowed to think this way" (7).

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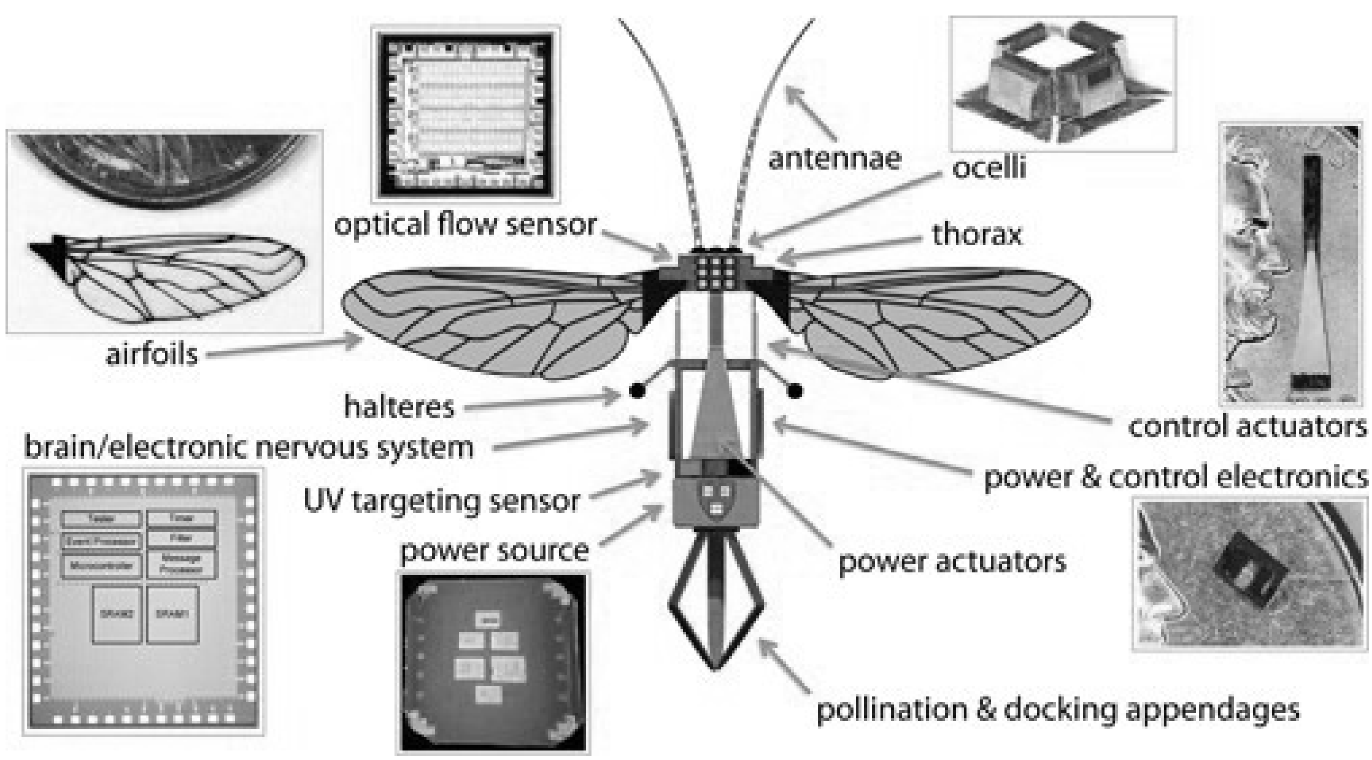
Additional support for the robobees comes from the Wyss Institute, a partner institute of Harvard University. Formally named the Wyss Institute for Biologically Inspired Engineering, the Institute was established by Swiss entrepreneur Hansjorg Wyss in January 2009 with a $125 million gift – the largest single philanthropic donation in Harvard's history (8). The Institute's purpose is to create "new materials and devices to transform medicine and create a more sustainable world" by undertaking and supporting "high-risk research and technology development" (8). Many of the professors on the Robobees team, such as Wood, serve as faculty at the Institute in addition to the University. Like the Robobees project, the Institute serves as a collaborative effort to produce technology inspired by biology – building "like the way nature builds" (8).

However, Wood points out that the combination of biology and engineering in the Robobees project is not unique. The tendency to look to nature for engineering inspiration has been growing over recent years, especially with biomimicry. Looking to the shape

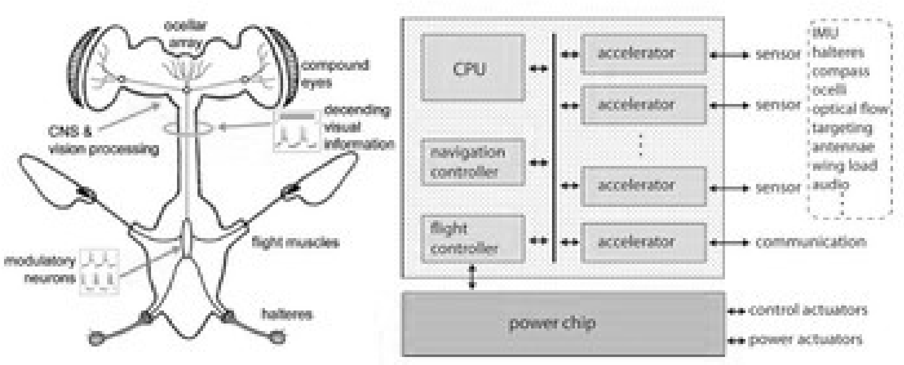


▲ **Figure 1.** The components of a robobee.

credit: http://robobees.seas.harvard.edu of a whale's flipper, for example, can motivate the creation of a more aerodynamic and efficient wind propeller (9). The benefits of this interaction are apparent, says Wood, as are the "analogies between organism and device" (7).

The Science of Mimicking the Bee

So how does one go from organism to device in the case of a honey bee? Bees are fascinating and complicated creatures in how they operate as individuals and communicate as a hive. With such complexity, replicating the function and behavior of the living bees requires an impressive amount of research and technology. The projected robobees, once finished, will contain a microprocessor that runs high-level functions. Simple circuits run basic functions like balance, and UV sessors in the eyes scan flowers for UV patterns. Digital cameras track objects around the bee to relay how fast and how far it's traveling relative to other objects. Engineered insect appendages like antennae let the robobees communicate with each other and navigate. The feet have three prongs that, in addition to collecting pollen, also lock into docking stations in the hive so the bee can recharge and upload data (4). All of these features must fit in a robot that will be the size of an almond.



▲ **Figure 2.** An illustration of the functions of an insect nervous system with a block diagram of the physical manifestation of the functions as they correspond to the inner workings of the nervous system.

credit: http://robobees.seas.harvard.edu

Because nothing like these bees has ever been created before, the team has to come up with new solutions for every step of the process, from the communication and coordination of the bees to the miniature computer on board (7). This offers the opportunity to expand the fields of engineering and computer sciences and to use the robots to better understand the bees they imitate. For example, as a result of work on the robobees, the researchers are developing a better understanding of insect flight, the flexural structure of insect wings, and the effects of turbulence (5). Similarly, studying honeybees' brains and behavior has provided models for new ways of thinking about computing based on an arthropod's neural structure (7). Wood describes the Robobees project as the chance to address the question, "What fundamental science can we explore?" Through the research done so far, Wood says the team has "exploded" their capabilities and are "developing new paradigms for creating complicated mesoscale robotic structures." Everything from the wings to the communications systems, he says, "we now know how to build them" (7).

The building process itself has been divided into three sections, each with its own team of researchers: the Body, the Brain and the Colony.

Body Building: Creating Autonomous Flight:

Work on the body of the robobee focuses mainly on the mechanics of bees and the fluid dynamics of their wings. The work is supplemented in part by breakthroughs already made by Wood and his Microrobotics Lab in 2007, when they had the first successful flight of a life-size robotic fly (5). One of the key features that must be incorporated into the design of the robobee's body is the need for autonomous flight. With the ability to fly on its own, the robobee can then be programmed to work with other robobees as part of a colony.

Research into creating the robobee body examines three main aspects. One is the aerodynamics and control of the wing and the robot's flight. In order to imitate a honey bees flight, researchers have to tackle the problem of wing morphology and its effects on flight performance. Insect wings change shape during flight, which in a case of a robot would mean sudden changes in the flight pattern that may not be predictable or controllable. It becomes important, then, to mimic the functionality and versatility of biological wings while still maintaining control over the robobee's course (10).

Aerodynamics ties into the second main aspect of research into the body of the robobee – design and fabrication of the flight apparatus (5). Creating the wings involves extensive understanding and experimentation of the biomechanical characteristics of insect flight, such as fluid dynamics, turbulence effects, and flexural stiffness of wings. In mechanical design, factors such as the scale and effects of the veins present, and the spatial distribution of the wings require extensive research (11,12).

Finally, in order to maximize the flight time and efficiency of the robobees, the robots need to have a high-energy, portable power source and electronic system that are also compact and lightweight. The robobees electronic system must incorporate and power the devices necessary for communication, surveillance, and detection. Thus, the weight of the electronics must be carefully balanced with the flight capabilities (5).

Inside a Bee's Brain:

Building a System of Surveillance and Communication:

The brain of the robobee must control the devices important for the bee's function. The goal, according to Wei, is to design a computing system that controls the robobee's flight, senses fellow robobees and the bee's surroundings, and allows for simple decision-making. This enables the robobee to fly autonomously, making its own adjustments and flight choices (5).

Moreover, the brain needs to run both the body and the colony aspects of the robobee. Here again, understanding the nervous system of the actual honey bee provides a model for the design of the robots. The robobees will have an electronic nervous system, sensors for proprioception and exteroception – the position of one's own body and of stimuli outside of the body, respectively – and control algorithms for determining courses of flight (5). All of these must be lightweight and efficient as well.

Constructing the brain of the robobee is no easy task. For example, making an exteroceptive network requires recreating the optomotor reflexes of insects, or the combined movements of their eyes, heads, and bodies that stabilizes their field of vision. A computer imitation of these reflexes performs the four major tasks relating to optomotor reflexes. These four major tasks are translational responses into pure translational optic flow, rotational responses to pure angular rotation, the combinations of both translation and rotation necessary to avoid obstacles, and yaw, or the movement of deviation from the direct course (13). In short, in order to interact with the outside environment, the robobee must be constantly taking in, processing through, and adjusting to information streaming through its sensors as it flies along its course.

"[B]ees are very good at doing all these complex tasks in a decentralized manner. They are all behaving individually, but together as a collective they achieve all those tasks. There's a whole consensus process happening at the hive. We're concerned with – how do you design this behavior?"

Honey, I'm Home! – Creating Communication in a Hive of Thousands

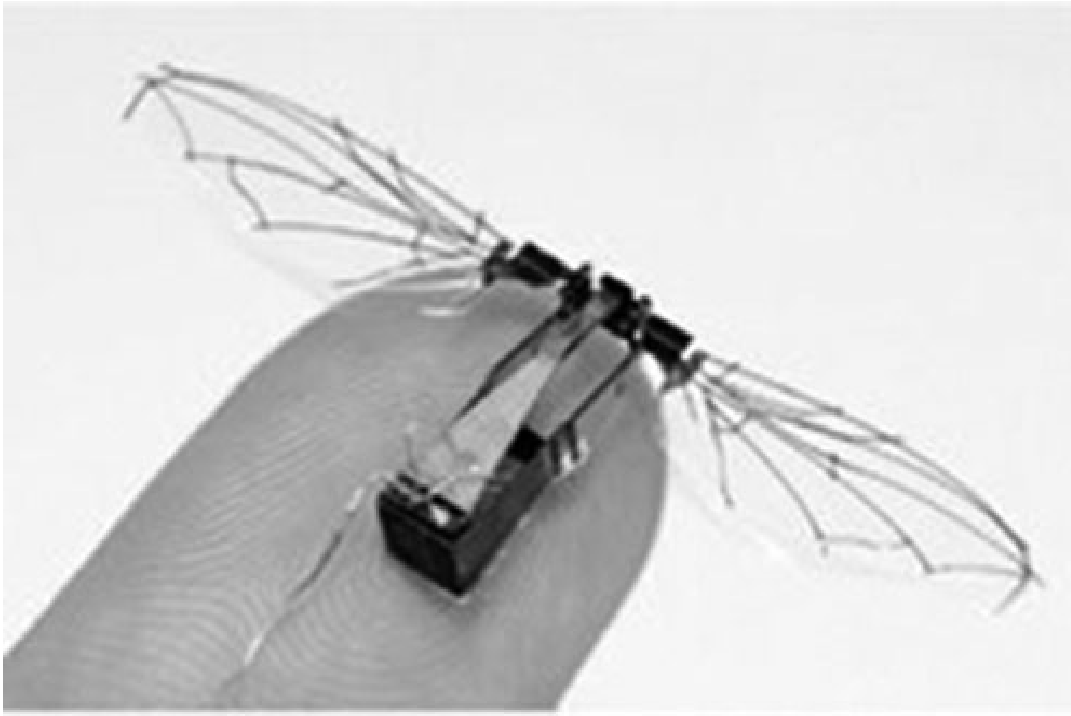
Finally, the robobee needs to operate within a colony, a swarm of hundreds to thousands of other robobees. While one bee may contribute only one pathway's worth of information or one flight's worth of pollination, collectively the hive can complete the entire surveillance or pollination of the area. Each robobee acting autonomously must still operate in such a way that it does not neglect a particular task or overlap with the operations of the other robobees.

As one of the members of the colony team, Spring Berman's focus is on how to control large groups of robots, particularly in crop pollinations. She is trying to develop a way of controlling the robobees so that "whether you have 100 or 10,000 it doesn't become more difficult to control the system" (6). This approach is referred to as "global-to-local," or a top-down system of communication (5). "Global-to-local" is also a model for how a real hive works. Honey bee hives behave in a decentralized manner, as there is no leader-designated tasks for each bee. "There's a queen," Berman explains, "but there's no leader telling the bees what to do. But bees are very good at doing all these complex tasks in a decentralized manner. They are all behaving individually, but together as a collective they achieve all those tasks. There's a whole consensus process happening at the hive. We're concerned with – how do you design this behavior?" (6).

Currently, the team is finding the solution by developing coordination algorithms (5,6). The algorithms represent task switching and can be

credit: http://www.roundrocktexas.gov/images/bees_large.jpg

▲ **Figure 5.** Honeybee colonies exhibit incredibly efficient and adaptive behaviors as a group, even though an individual bee is tiny compared to the world it lives in. Achieving the sophistication of social insect colonies poses a number of challenges.



▲ **Figure 4.** A life size robotic fly (a precursor to the robobee) placed on a human finger.

credit: http://robobees.seas.harvard.edu

used to calculate the certain probability the robobee will choose one of two tasks (6). This decision-making within the swarm results in movement similar to that of molecules in a chemical reaction. Researchers can then model the algorithms like a chemical reaction and solve them numerically (14, 6). The robobees will have a flight-time of a few minutes before they need to return to the hive for recharging (6). With these algorithms, the team can model the flight of the swarm and ensure that, through the decision-making of each individual robobee the swarm as a whole pollinates an entire field through the process of a few flights.

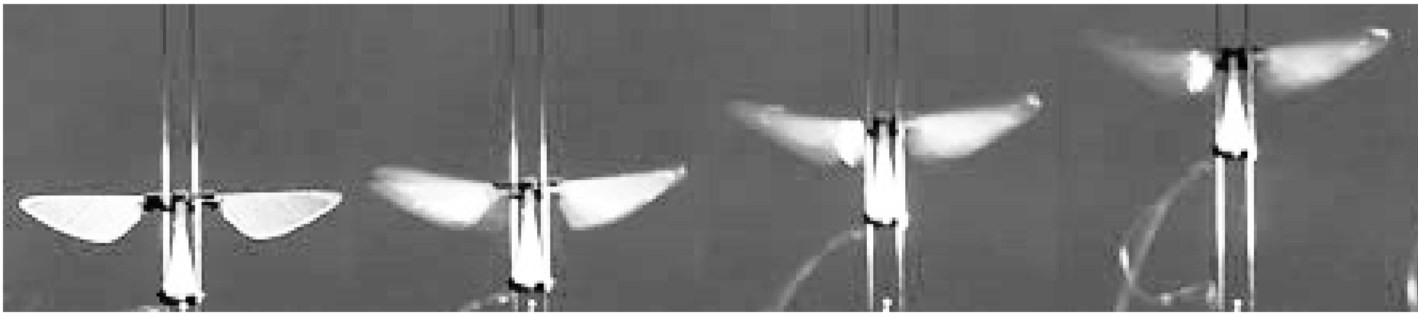
For the global-to-local approach, the goals of the colony need to be translated into individual robobee's decisions. The task-switching algorithm will help accomplish this procedure. But the global-to-local approach also means that goals, such as crop pollination, can be given to the colony and then translated down into goals for each of the individual bees. Additionally, the system needs to be able to "re-optimize," or adapt its objectives, as the environment changes (5). The top-down system of communication and task delegation needs to function cohesively for the parallelism, energy efficiency, and strength of the hive's operations. Ultimately, the swarm will be efficient in using flight time for exploring larger areas, effective in communicating and dividing up tasks, and robust in compensating for the potential errors of individual robobees (5).

Putting the Bees to Use – The Practical Applications of a Robobee:

The finished robobees will, of course, be capable of pollination and beneficial to the agriculture industry. As Berman explains, a farmer will be able to purchase hives of bees and place them in strategic areas of his or her fields. The robobees will be programmed to take flight in short intervals and pollinate all areas of the field within a few trips, coming back to the hive to recharge and receive flight-plan information (6). Wood stresses, however, that he is "not claiming these [robobees] will replace bees" (7). CCD will still be a serious problem. The robobees will be useful in providing technological substitutes to keep food production operating while researchers try to understand and solve the causes and effects of CCD.

Beyond pollen collecting, the robobees will have many other potential applications. Because of their size and their communication and surveillance capabilities, robobees could be extremely useful in search and rescue operations. They would be able to fit into places, such as a pile of debris after an earthquake or hurricane, that would otherwise be too small or too dangerous for humans or animals. For example, fire fighters can use robobees in their work to locate the whereabouts of survivors before putting themselves at risk entering a burning house (7). Similarly, the bees would be useful and potentially life-saving on military operations. They could collect surveillance of areas with much less risk of being detected and with no risk of human casualities. In fact, the U.S. Air Force already awarded a grant in 2008 for Wood's work on "the aero-elasticity of flapping wings of micro aero vehicles," a precursor to the work going on now with the robobees (15).

The robobees' data collecting capabilities would make them useful in more day to day applications as well. Robobees could be helpful with traffic monitoring, or for use in other scientific projects such as weather and climate mapping (5). Additionally, Wood states that there are many other potential applications that may not be apparent yet. The new science developed in the process of creating the bees could provide a multitude of information and technologies that will be useful in other scientific settings. Recognizing these potential opportunities is an aspect that benefits from the project's connection with the Wyss



▲ **Figure 5.** Images of a robotic fly, a precursor to the robobee, taking flight.

Institute. As Wood explains, the researchers at the Institute work to facilitate a "transformation of ideas to applications we might not have envisioned." One possibility Wood mentions, for example, is the potential offshoot from the Robobees project to future medical applications (7).

The robobees will be designed to be simple, disposable, and affordable in order to make purchasing and employing mass quantities of miniature robots feasible. Right now, a large amount of money is going into creating the bees, which is very time and people intensive. The NSF's Expeditions in Computing program awarded the Robobees project a grant of $10 million over five years in 2009 to fund this portion of the robobees production (16). The goal of the NSF fund, as Wood explains, is to get the bees to do something simple. Wood notes that the team is still working on the fundamental challenges and logistical questions surrounding the creation of the first robobees. The team foresees the robots will be capable of flight under controlled lab conditions in the next three to five years. In the following two to three years, the bees will be capable of flight outdoors. Within the following ten years, the bees are projected to be ready for commercial production. Once the project reaches that stage, the bees will be readily available and affordable. The materials used to produce the bees are relatively cheap, at approximately a few dollars per bee currently. "We're not using any platinum coating," Wood jokes. Purchasing and using the robobees should be a practical option for the farmers, firefighters, and others who could benefit from them (7).

Conclusion:
Where the bees are now

Although the robobees are still in the preliminary stages of research, already the program is contributing not only to the scientific and engineering fields but also to the greater non-scientific community as well. One of the main aims of the robobees program is to "teach and inspire future scientists and engineers" (5). The research team has undertaken outreach programs in the greater Boston community to give children the chance to learn about the robobees and the science behind them. Graduate students involved in the project have gone into public schools in the Boston area to give child-friendly presentations on the robots, and the biology and engineering behind them (17). The team is also in the process of creating an interactive exhibit with the Museum of Science in Boston (5). "This project provides us with a really nice, tangible outlet for education," Wood explains. And the children "get it," he says. "They get how all these pieces work together and what they would do" (7).

On the note of education, Wood, when asked if there was anything else people should know about the project, added in a call for undergraduates interested in research. "We're always interested in undergrad help," Wood said. "We've had great success with undergraduate research. Tell them to come talk to me." So, if getting these robobees off the ground sounds like something you are interested in, here is your chance. H

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