ROBO-TIC: THE DEVELOPMENT OF A TICK-ELIMINATING ROBOT

JAMES SQUIRE, CHRISTOPHER BABER, BENJAMIN ABSHER, AND THOMAS KENDZIA

CROSSHAIRS COURTESY OF BEN EARWICKER (WWW.GARRISONPHOTO.ORG). TICK COURTESY OF WIKIMEDIA COMMONS/U.S. DEPARTMENT OF AGRICULTURE

Tick bites are a calculated risk of enjoying outdoor activities; yet in certain geographic regions, deer ticks are more likely than not infected with Lyme disease even to the extent that some medical journals recommend physicians automatically begin antibiotic treatment following bites in high-risk areas regardless of a patient's symptoms. There exists no Lyme vaccine approved for use in humans, and annual reported cases in people are rising with the spread of infected ticks across the northeast United States.

Undergraduate electrical and mechanical engineering students from the Virginia Military Institute (VMI) have developed a tick-control robot that uses biomimicry to encourage ticks to attach to a pesticide-infused fabric patch. A prototype was found to remove 45 ± 4 out of 50 ticks seeded in a small and noncontrolled study by Woulfe et al. A ruggedized prototype was next developed by engineering students from both VMI and Washington & Lee University capable of withstanding a multiweek controlled study by an independent environmental testing laboratory while students from Wake Forest University examined how to commercialize the device.

Tick-vectored illnesses: A growing threat

Tick-borne illnesses are the most common of vectored diseases in the United States, according to the U.S. Centers for Disease Control and Prevention (CDC) and, for reasons not fully understood, they are becoming increasingly common. The CDC reports that Lyme disease, carried exclusively by the blacklegged or deer tick, almost doubled in the past decade (see Fig. 1), and other studies indicate that high-infection regions are growing in size.

Digital Object Identifier 10.1109/MPOT.2013.2255736
Date of publication: 6 March 2014

Although the number of confirmed cases does not appear high for a country with a population of approximately 300 million, it is uncommon to be officially diagnosed with Lyme disease in a manner that the CDC recognizes, and therefore only a small percentage of actual cases are reported. Many other diseases less well known as Lyme but potentially more lethal can be transmitted via ticks, such as babesiosis, ehrlichiosis, Rocky Mountain spotted fever, and anaplasmosis.

The increased human incidence rate of Lyme disease is, as expected, roughly proportional to the increasing area of ticks infected with the bacteria, yet it is difficult to control tick populations. The only mechanism widely employed involves spraying tick neurotoxins such as permethrin in the habitat of tick hosts. While this is very effective, most states restrict permethrin spraying to certain areas since it is toxic to a number of species other than ticks including cats, fish, and certain waterfowl. A recent government study funded by the U.S. Army Medical Research Command further implicates permethrin in causing Gulf War Syndrome.

A robotic solution

We developed a method to reduce tick populations using robotics and biomimicry. To understand how this is done, it is necessary to describe the habitat and hunting practices of ticks. Ticks are not uniformly spread throughout the homeowner's property but rather are much more likely to reside along a relatively narrow strip separating manicured lawn from the surrounding woods. Some studies indicate that 82% of the tick population lives within 3 m of this border called the "ecotone." Although ticks have limited mobility, they can move within the ecotone to maximize the probability of locating a host and then drop on it or raise their spiny legs to become ensnared in the host animal's fur as it brushes by. Ticks have evolved extraordinary sensory capabilities to find hosts; they respond to vibrations from a field mouse running along the forest floor a meter away, changes in temperature from a passing mammal's body heat, and can sense the elevated levels of carbon dioxide (CO_2) in exhaled breath that falls to the ground after an animal has passed.

To mimic an animal trail, we placed a hollow tube in the ecotone that slowly emits CO_2 in regular intervals through small holes drilled through the wall, as seen in Fig 2. Within 30 min, ticks consolidate from the ecotone to within a few inches of the tube. The tube also houses a wire that emits a low-frequency magnetic field. The robot senses the field and travels around the tubing, dragging a denim skirt behind it infused with an acaracide such as permethrin. The ticks sense the vibration and the slightly elevated, friction-induced temperature of the skirt and allow spiny projections on their legs to ensnare the denim fibers. This entanglement prevents them from being easily brushed off as the skirt is dragged in the same manner as when they attach to small rodents. Although the ticks only stay attached for a minute or two before recognizing their mistake, in that time they absorb enough permethrin to kill them within 24 h. Except for a miniscule amount absorbed by the ticks or rubbed off in leaf litter, the permethrin remains on the skirt and, unlike traditional spraying, does not contaminate the environment.

We constructed a prototype robot to determine if this approach would work. Using the methods described above, it was tested in a 10-m diameter lawn seeded uniformly with ticks and proved effective at removing 45 ± 4 out of

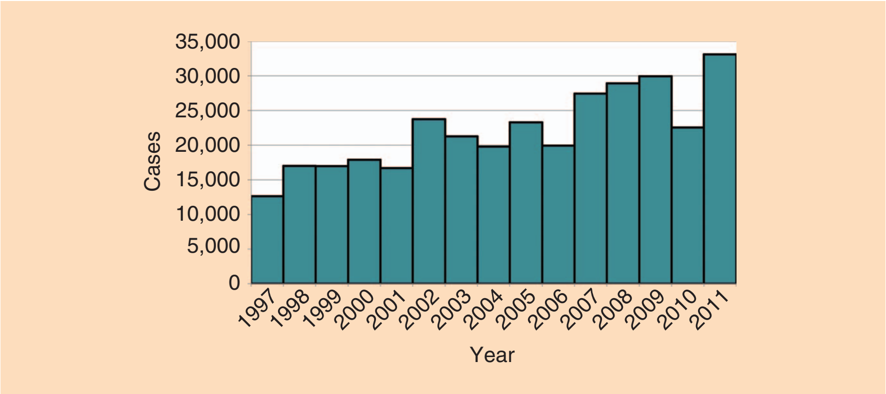

Fig. 1 Lyme disease rates in the United States from 1997 to 2011. (Data from the CDC.)

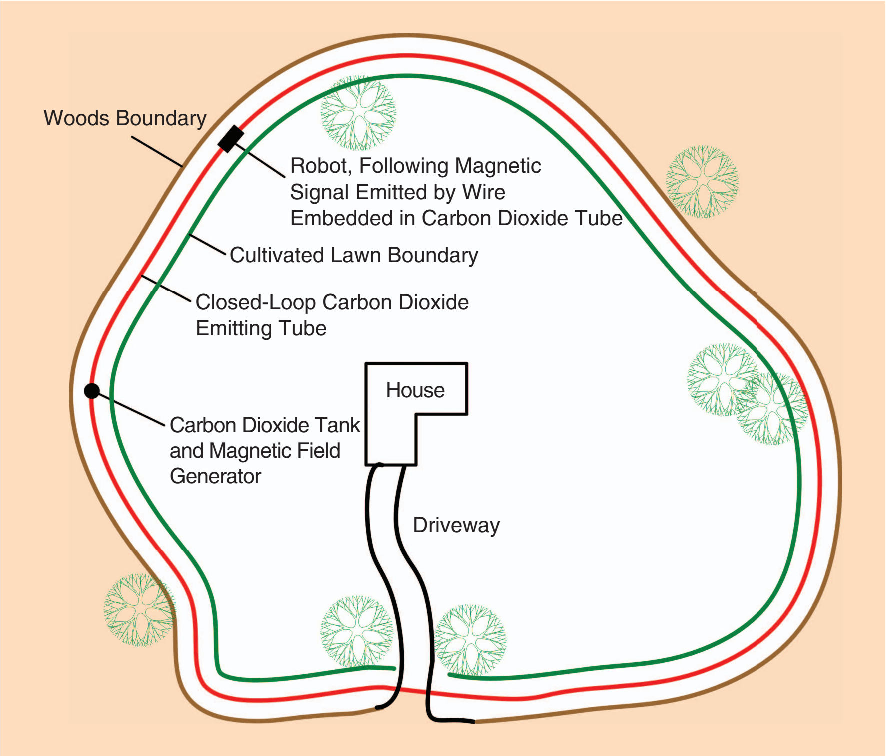

Fig. 2 The experimental setup. A robot autonomously follows a carbon-dioxide-emitting tube around the periphery of a lawn. Ticks are drawn to the tube area and attach to a pesticide-embedded skirt dragged behind the robot.

Fig. 3 A second-generation environmentally hardened robot pulling the tick-collection skirt.

50 ticks in a small uncontrolled experiment at Old Dominion University in the laboratory of Daniel Sonenshine, one of the inventors. Sonenshine has experience with a number of methods of tick collection as the author of *Biology of Ticks* and noted it was among the most successful methods he has observed, but the prototype was not mechanically robust and it was unable to operate autonomously for more than about 10 min at a time. This article describes the design of a more robust robot, capable of withstanding harsher environmental conditions unattended and fielded and serviced by non-engineers.

TICK-BORNE ILLNESSES ARE THE MOST COMMON OF VECTORED DISEASES IN THE UNITED STATES, ACCORDING TO THE U.S. CENTERS FOR DISEASE CONTROL AND PREVENTION AND, FOR REASONS NOT FULLY UNDERSTOOD, THEY ARE BECOMING INCREASINGLY COMMON.

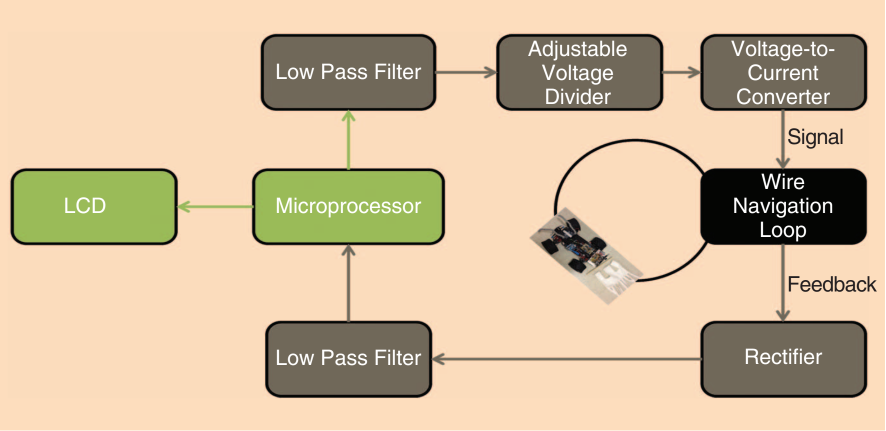

Fig. 4 The base station, whose output creates a magnetic field along wires embedded inside the CO_2-emitting tick-attraction tube for robot navigation. Digital signals are shown in green and analog signals in brown.

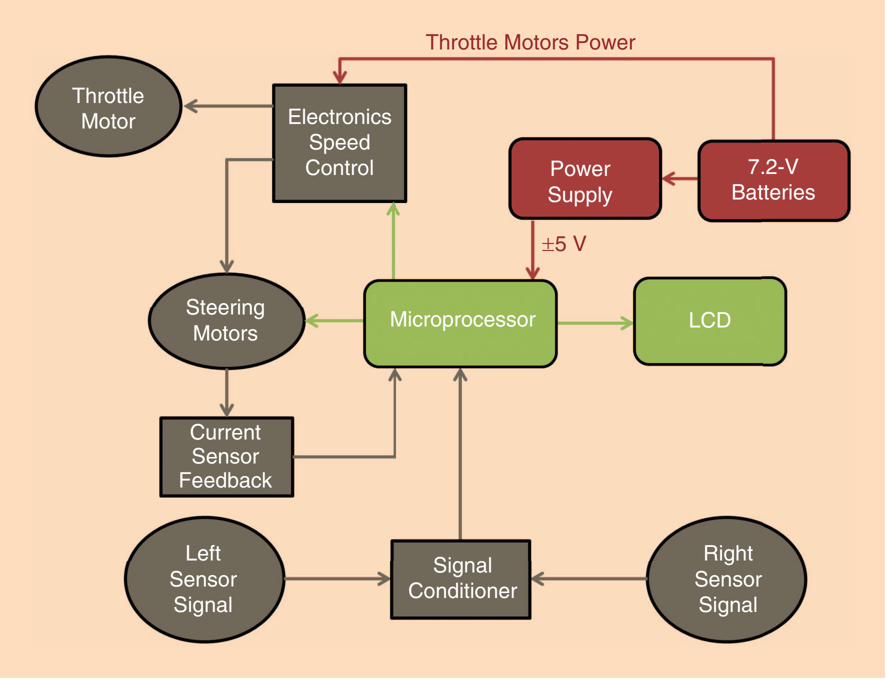

Fig. 5 The tick robot signal diagram. Digital blocks are in green, analog in brown, and power in red.

The second-generation tick-collection robot system shown in Fig. 3 incorporated numerous mechanical and software changes to the robot and changes to the frequency generating base station. Mechanical changes reduced the likelihood that the robot would become disabled while navigating. Long-travel shock absorbers, larger diameter tires, an articulating chassis, and four-wheel drive permit any wheel to lift 25 cm above the plane of the remaining three tires while torque is applied to all four wheels. Locking front and rear differentials enable the torque to be redistributed equally to three wheels should one encounter a full-slip ground condition. Four-wheel steering was added to drop the turning radius less than the width of the chassis, and the drive motors and electronics cabinet were weatherproofed to allow the robot to operate in wet conditions.

Since it is impossible to design a robot that never becomes stuck due to environmental obstacles, sensors were added to detect a range of failure modes including the robot being flipped over, the steering mechanism becoming fouled by high grass, the robot navigating away from the CO_2-emitting tubing and navigation wire, or the robot becoming stuck in a hole. The software was modified to include a time-limited spiral-based search routine if it should lose contact with the navigation wire and a shutdown and audible signaling routine for all other conditions.

Base station

The base station houses a frequency generator and an amplifier to create a magnetic field for the robot's tracking sensors that enable it to follow the CO_2 tube (Fig. 4). A microcontroller (ATMega328P) generates a 7-kHz 0–5 V square wave, whose fundamental sine wave is isolated by an 8th order Butterworth filter. The current is then increased by a set of parallel op amps, which then flows into a wire located inside the CO_2 tubing. The current, and therefore the magnetic field strength, is monitored by passing the signal through a small sense resistor, whose voltage is amplified, rectified, and sent through a low-pass filter, whose dc voltage is routed to the microcontroller.

Robot

The schematic in Fig. 5 shows the signal and power interaction of the tracking sensors, the steering and throttle motors, the power, LCD display screen, and the microcontroller. The 7.2-V batteries supply power to the microcontroller via a power conditioner and both motors. The left and right sensors receive a signal from the magnetic field and convert this signal to a dc output, which is sent to the microcontroller. The microcontroller properly adjusts the steering motors using a proportional-derivative controller to navigate directly over the CO_2 tubing.

Located at the front of the robot are right and left tracking sensors that allow the robot to follow the CO_2 tubing around the ecotone. Each tracking sensor is composed of an inductor that develops a voltage whose amplitude is a function of its distance to the navigation wire connected to the frequency generator. This signal is amplified by a differential $\times 100$ instrumentation opamp to a voltage of ± 2 V, which is then rectified and low-pass filtered to provide a dc voltage proportional to signal strength. This signal is read by twin A/D converters in the microcontroller, which is then processed by a fuzzy logic algorithm to produce navigational information sent to the steering servos and the main drive motor.

The steering motors circuitry was designed to provide a feedback voltage to the microcontroller proportional to the current used by the steering servos. This feedback is used to alert the navigation program and ultimately the user if the steering mechanism becomes stuck, which is a possibility as the robot navigates tall grass. The current is measured by a small value sense resistor, which is amplified by an operational amplifier and low-pass filtered, and then sent to a A/D port on the microcontroller.

Commercialization

One of the challenges students faced while constructing the second-generation robot involved understanding how the device could be commercialized, who the eventual end-users would be, and understanding the needs of users who will likely not be engineers or biologists. The students engaged Elizabeth Baker, entrepreneurship professor from Wake Forest University, and her business students. Baker suggested that the engineering students first raise some seed capital from their university's foundation to patent the device, which they did, and then arrange to test the system with an independent laboratory when the ruggedized device was completed. She also advised the students to consider seeking licensure of the intellectual property under the business model of it being used by small independent businesses, since major pest control companies do not have an existing technology infrastructure capable of supporting a robotics business, and allow the independent businesses autonomy to decide whether to pursue small private contracts from homeowners or larger contracts from local, state, or federal agencies for parks or military training facilities.

Baker conveyed concern under this business model for safety issues associated with the use of permethrin and recommended that the team develop protocols for small business owners that describe how to apply, store, and dispose of the chemical. For instance, when working with the permethrin-soaked denim skirt, the protocol requires the user to wear gloves, describes how to mix concentrated permethrin with water, how to load it into spray bottles, and how to apply it to both sides of the denim skirt. After the robot completes its tick removal process, the protocol specifies that the denim skirt should be stored in a sealed plastic container at room temperature. Since brushes are used to remove ticks and debris from the skirt, the protocol also describes how to properly dispose of these brushes in accordance with U.S. Environmental Protection Agency guidelines.

ONE OF THE CHALLENGES STUDENTS FACED WHILE CONSTRUCTING THE SECOND-GENERATION ROBOT INVOLVED UNDERSTANDING HOW THE DEVICE COULD BE COMMERCIALIZED, WHO THE EVENTUAL END-USERS WOULD BE, AND UNDERSTANDING THE NEEDS OF USERS WHO WILL LIKELY NOT BE ENGINEERS OR BIOLOGISTS.

Testing and future work

The engineering student team arranged testing at the Calder Environmental Field Laboratory at Fordham University during the summer of 2012. Unfortunately, Calder experienced one of the most intense droughts since 1962, which killed enough of the available tick population to make it impossible to test whether the robot was able to further reduce the tick population. Nevertheless, the engineering portion was a success, and the robot logged no mechanical or electronic failures during two weeks of field tests.

Two additional weeks of field testing were performed by Old Dominion University in the summer of 2013 comparing areas that were robotically treated with or without the permethrin skirt attached with manually harvested post-treatment tick densities in heavily wooded areas. These data in a paper currently under review show a statistically significant reduction in tick densities from 75 to 100% depending on the trial and other experimental variables. Unfortunately, the deep woods areas had essentially infinite reservoirs of ticks on either side of the 1-m wide treated path, and in 36 h tick densities returned to near pretreatment levels, indicating the unsuitability of the robot to clear large areas uniformly seeded with ticks.

Residential areas however are not uniformly seeded. Ticks rarely live in manicured sections of lawn but, as earlier noted, prefer the narrow ecotone strip of low brush, mulch, and leaf debris separating manicured lawns from untended woods or separating adjacent properties in suburban areas. We therefore plan an additional series of tests for the summer of 2014 in which the robot will treat suburban-style adjacent properties with relatively narrow ecotones to determine how long it takes ticks to repopulate once their local populations are exhausted.

If these tests are successful, the students hope to raise enough capital to make and sell several to business people interested in providing tick-removal services. As ticks do not migrate large distances, a treated property is expected to stay relatively tick-free for at least one tick life-cycle, which is about two years. Half-acre suburban lots that are typical in many high-risk areas of the northeast require about 150 m of tubing laid on the surface around the perimeter and take about 15 min for the robot to traverse. Preliminary trials indicate the weighted tubing takes less than 30 min to reel out by walking around the 150-m perimeter. Initial CO_2 seeding takes an additional 30 min, and four traverses by the robot would take an hour. If the tubing takes an additional 30 min to reel up, a house could be treated in less than 3 h, for the cost of labor plus US$15 of CO_2 and a battery charge.

Even if successful, the question remains whether it will work well enough to make a noticeable impact on rising tick populations. The CDC has reported a three-fold rise in Lyme disease infections in the past

20 years, and this trend appears to be continuing. It is our hope that robotic technology may provide one way to reverse this trend in an economically-efficient manner without leaving potentially harmful pesticides in the environment.

Read more about it

- P. W. Rand, E. H. Lacombe, R. Dearborne, B. Cahill, S. Elias, C. B. Lubelczyk, G. A. Beckett, and R. P. Smith Jr., "Passive surveillance in Maine, an area emergent for tick-borne diseases," *J. Med. Entomol.*, vol. 44, no. 6, pp. 1118–1129, 2007.
- M. A. Diuk-Wasser, A. G. Hoen, P. Cislo, R. Brinkerhoff, S. A. Hamer, M. Rowland, R. Cortinas, G. Vourc'h, F. Melton, G. J. Hickling, J. I. Tsao, J. Bunikis, A. G. Barbour, U. Kitron, J. Piesman, and D. Fish, "Human risk of infection with Borrelia burgdorferi, the Lyme disease agent, in Eastern United States," *Amer. J. Trop. Med. Hyg.*, vol. 86, no. 2, pp. 320–327, Feb. 2012.
- J. H. Woulfe, G. B. Hammond, D. J. Crump, D. L. Livingston, and J. C. Squire, "Robotic tick killer," *IEEE Potentials*, p. 18, Jan. 2006.
- (2013, Mar.). Tickborne diseases of the US. [Online]. Available: http://www.cdc.gov/niosh/topics/tick-borne/
- (2012, Sept.). Lyme disease. [Online]. Available: http://www.cdc.gov/lyme/stats/chartstables/casesbyyear.html
- L. Steele, A. Sastre, M. M. Gerkovich, and M. R. Cook, "Complex factors in the etiology of Gulf War illness: Wartime exposures and risk factors in veteran subgroups," *Environ. Health Perspect.*, vol. 120, no. 1, pp. 112–118, Jan. 2011.
- K. C. Stafford. (2007). Tick Management Handbook (Technical Bulletin 1010), The Connecticut Agricultural Experiment Station, New Haven. [Online]. Available: http://www.ct.gov/caes/lib/caes/documents/publications/bulletins/b1010.pdf
- D. E. Sonenshine, *Biology of Ticks: Volumes 1 and 2*. New York: Oxford Univ. Press, 1992.
- Robotic pest-removal system, U.S. Patent 7 441 367, James C. Squire, Oct 28, 2008.

About the authors

James Squire (squirejc@vmi.edu) is a professor of electrical engineering at the Virginia Military Institute. He earned his B.S. from the U.S. Military Academy and his Ph.D. from the Massachusetts Institute of Technology. He was awarded a Bronze Star in the Army during Desert Storm and was selected as Virginia's Rising Star professor in 2004. He is a licensed Professional Engineer in Massachusetts and Virginia and maintains an active consulting practice.

Christopher Baber (baberwc@mail.vmi.edu) joined the Virginia Military Institute as a business major and switched during his sophomore year to electrical engineering. Following graduation, he will attend the U.S. Navy Nuclear Power School to become a submarine officer.

Benjamin Absher (absherb12@mail.wlu.edu) earned his B.S. in physics at Washington and Lee University. He currently works for Alarm.com in Vienna, Virginia, as a product management associate.

Thomas Kendzia (kendziata@mail.vmi.edu) earned his B.S. from the Department of Electrical and Computer Engineering at the Virginia Military Institute. He currently works for Thomas and Betts, designing uninterruptable power supplies in Richmond, Virginia.

Digital Object Identifier 10.1109/MPOT.2014.2305253