A Biobotic Distributed Sensor Network for Under-Rubble Search and Rescue

Alper Bozkurt, Edgar Lobaton, and Mihail Sichitiu, North Carolina State University

Utilizing the latest neural engineering developments, researchers have enabled biobotic insects that would function as search-and-rescue agents to help map under-rubble environments and locate survivors and hazardous conditions.

After a disaster, the survival of victims trapped under rubble often depends on how quickly they are found, rescued, and treated. First responders use search-and-rescue techniques such as canines, listening devices, and radars, which search the rubble's near-surface regions.[1] However, complementary techniques are needed to penetrate the smaller gaps and voids deep in the rubble.

Distributed systems are indisputably superior for tasks such as exploration, mapping, and large-area sensing. Recent achievements in swarm robotics, a new multirobot coordination–system approach, have been inspired by observations of emergent collective behaviors among insects. In swarm robotics, multiple smaller-scale robots interacting with one another and the environment could coordinate their actions to help manage the under-rubble environment's uncertain and dynamic conditions. The following hypothetical scenario demonstrates the capability of such an under-rubble robotic sensor network.

A major earthquake hits an urban environment, and several survivors are trapped under the collapsed ruins of a 20-story building. Time is short and limited tools are available for removing debris. A special first-responder team arrives with a set of insect-sized robots, which they drop at the edge of the rubble pile. These robotic agents carry tiny radios on their backs that, together with other sensors, measure the distance between the agents to localize them with respect to a few reference points. As the robotic agents crawl through the rubble, their task is to keep moving while staying within a certain distance of one another to maintain the radio network.

The agents' tiny environmental sensors, including microphones and infrared or gas sensors, monitor the rubble for dangerous gas leaks or victims' cries for help. The swarm moves collectively from one end of the rubble to the other. During this

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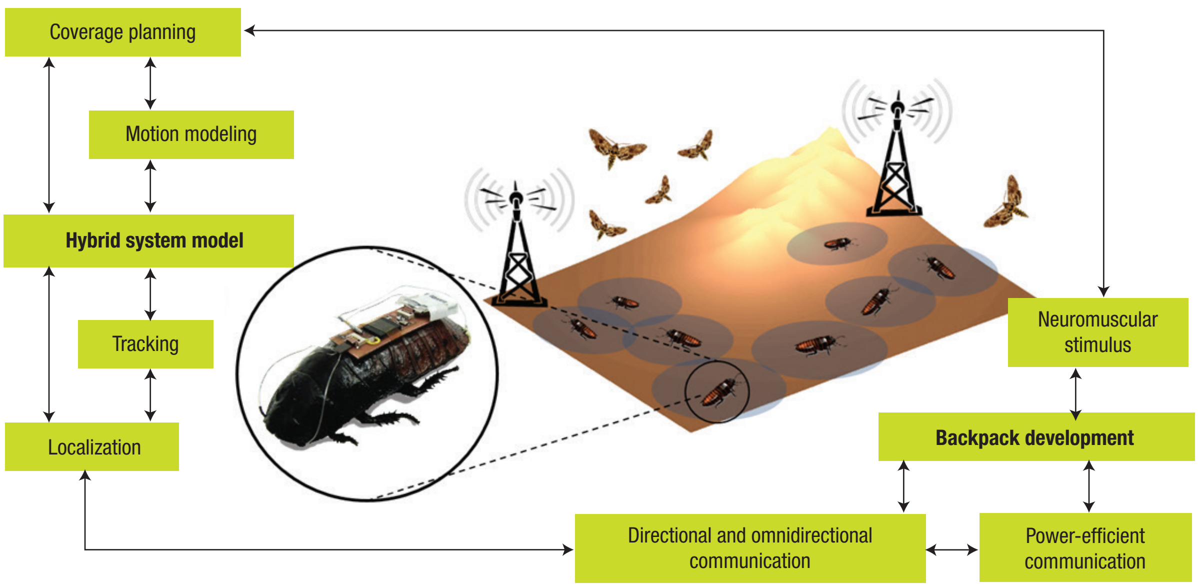

FIGURE 1. System-level overview of the Cyborg Insect Networks for Exploration and Mapping, or CINEMa, project.

sweeping action to find survivors, each robotic agent's location is used to map the under-rubble environment. Finally, one of the agents locates a suspicious sound signal 30-m deep, but it is almost impossible to transmit this information outside the pile of concrete and steel to the first responders. So, the autonomous radio network finds a multihop route, which allows the information to be sent from one agent to another, all the way to the mission control center outside. Mission control establishes a radio link with the survivor, assesses her health situation, and informs her that help is on the way. The first responders determine the shortest route to the victim and concentrate their digging efforts in that direction.

This might sound like a scene from a science fiction movie. But as part of the Cyborg Insect Networks for Exploration and Mapping (CINEMa) project at North Carolina State University, we have been working to establish the fundamental physical and algorithmic building blocks of such a sensor network for under-rubble environments (see Figure 1).

MOBILE SENSOR NODES AND BIOBOTIC AGENTS

In under-rubble reconnaissance, the success of distributed robotic systems depends highly on the robotic agents' capability to cope with the uncertain and dynamic environmental conditions that make navigating through rubble notoriously difficult. Although a number of centimeter-scale insect-like robots have been demonstrated successfully,[2] current technology falls short in offering mobile robotic agents that function effectively under these adverse conditions. Until synthetic robots become practical for use in disaster situations, an alternative solution is to instrument real insects for this purpose.[3,4] Cockroaches, for example, exhibit an unmatched ability to navigate narrow passages under rubble, climb rough surfaces in any direction, and maintain control and stability during perturbations.

We have used the latest neural engineering and neuromuscular stimulation techniques to exploit the locomotory advantages of insects as biobotic search-and-rescue agents. From the 12 cockroach species reared in North Carolina State University's entomology department, we selected *Gromphadorhina portentosa*—the Madagascar hissing cockroach—as our model insect. Its relatively large size and slower speed allow for larger payload capacities and easier biobotic manipulation of its locomotion. This species is also relatively easy to rear and maintain and is available commercially in many US pet stores.

Several locations within the roaches' peripheral nervous system can be stimulated to bias their natural locomotory behavior. We selected the antennae as the target location for neurostimulation. Cockroaches naturally formulate their escape responses to avoid obstacles by using their antennae's tactile guidance, because the optical cues detected with their eyes might not be processed fast enough.[5]

BIOBOTIC CONTROL DEMONSTRATIONS

We surgically implanted fine wire electrodes into the antennae to apply stimulation pulses wirelessly through a backpack with an RF link. By sending right- and left-turn commands via a manual remote controller, a human

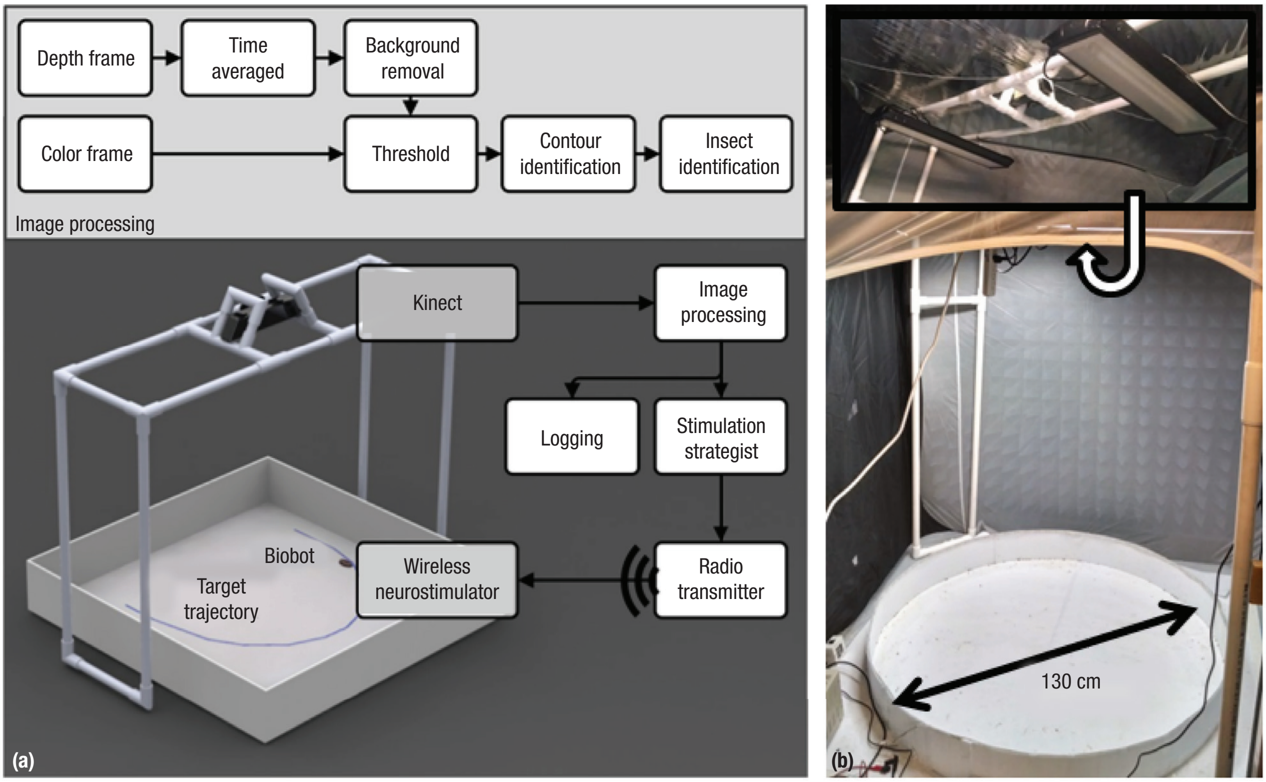

FIGURE 2. Diagrams of the (a) Kinect-based automated biobot evaluation platform and (b) anechoic chamber in which the biobot evaluation experiments are performed.

operator can guide the insect biobot along an S-shaped line pattern drawn on the floor.[6] To automatically and objectively evaluate the insect biobots, we constructed a test platform using a Microsoft Kinect sensor.[7] A PC connected to the Kinect locates the insects using the video feed and automatically steers the insects along a predetermined test path by sending neurostimulation pulses wirelessly (see Figures 2 and 3). The Kinect also allows us to conduct experiments in the dark—when the insects are more active—by providing infrared-based depth images.

Using this setup, we tested the insects' biobotic capabilities in a maze environment; their task was to follow a defined path between the start and finish points (see Figure 3). The walls and corners of the maze served as an extra challenge to distract the insect biobot from completing the task, because cockroaches are naturally attracted to cool, dark areas and tend to stay close to wall corners.[8] The aim was to demonstrate that the biobots could complete the assigned tasks despite external environmental factors and their natural behavioral response to these.

Because insects are experts at navigating the small gaps and voids under rubble, a useful biobotic search strategy is to keep the insects moving naturally and in random directions within a defined region. Holding the biobot's position within a particular region of interest and gradually moving the location of this region enables the biobotic swarm to scan the entire pile of rubble. We defined virtual fences in the test platform, much like the invisible fences designed to keep pets in a yard.[8] The Kinect sensor-based computer program detects the insect's position with respect to the virtual perimeter. The insect is turned around by the PC through a set of automated stimulation pulses (see Figures 2 and 3). In real-life scenarios, localization technologies (which we describe later) will replace the Kinect sensor to guide insect biobots to regions of interest. This capability is also critical to ensure that the biobots stay within the reception range of one another's radios to maintain the communication network.

BACKPACK TECHNOLOGIES FOR BIOBOTS

For neurostimulation-based locomotion control, environmental sensing, localization of biobotic agents, and communication with first responders, we developed a miniaturized wireless electronic backpack (see Figures 1 and 4). To minimize the cost of a multiagent swarm, we used a commercial off-the-shelf system-on-chip (SoC) solution from Texas Instruments (TI CC2530) that combines analog, digital, and mixed signals with RF functions on a single substrate level. TI CC2530 is tailored for IEEE 802.15.4/ZigBee and ZigBee RF4CE applications; it combines an 8051 microcontroller with a high performance RF transceiver while providing 8 Kbytes of RAM and up to 256 Kbytes of flash memory. This solution is adequate for our particular applications thanks to the availability of 21 general-purpose I/O pins and eight channel 12-bit analog-to-digital converters to connect to external devices. Table 1 presents the specifications for an ideal biobotic backpack.

Our experiments indicate that *Gromphadorhina portentosa* biobots have a payload-carrying capacity of up to 15 g.[9] The assembled backpack weighs 300–800 mg without batteries, depending on the number of sensors used. We generally use a lithium-polymer battery with a capacity of 90 mAh (weight: 2 g) or 20 mAh (weight: 400 mg), depending on the experiment duration. The backpack's power consumption ranges from 5 to 75 mW, depending on the duty cycling of the radio transmission and the number of sensors deployed. We have also implemented backpacks with solar-charging capabilities; using the aforementioned invisible-fence strategy, we can guide the biobots to a bright light source, which recharges the batteries in 10 to 30 minutes (see Figure 4).[8]

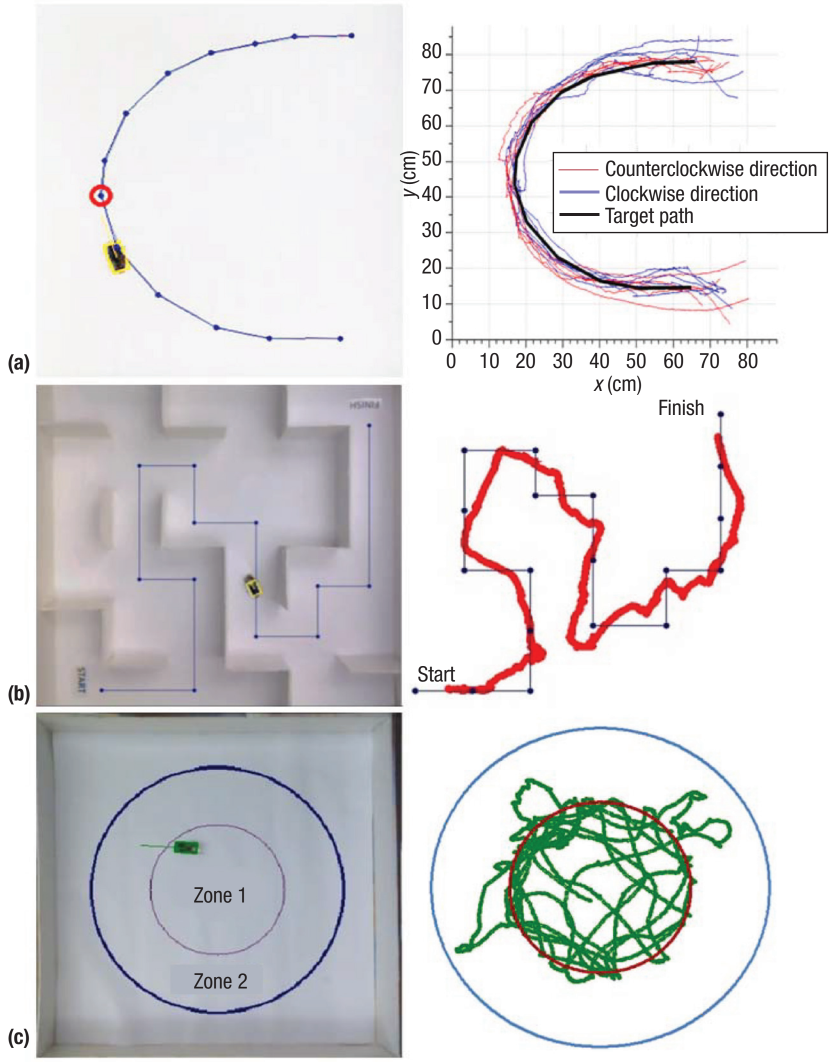

FIGURE 3. Sample results of three automated Kinect-based evaluation experiments: (a) U-line in an empty arena, (b) maze arena with erected walls, and (c) invisible fence in an empty arena. For the invisible fence, the Kinect-connected computer commands the insect biobot to make a U-turn when it is outside the boundary of zone 1 to ensure that it will always stay within zone 2.

SENSORS FOR DISTRIBUTED SENSING AND LOCALIZATION

We mounted a miniature custom microphone array on the backpack to allow detection and localization of sound sources to autonomously localize victims under rubble (see Figure 4). We connected three directional microphones to the backpack and sampled the signal at a rate of nearly 2 kHz. We used the sound's relative intensity to determine its direction; the biobot then autonomously steered toward the sound source (see Figure 5). We also demonstrated voice-transmission capabilities by replacing this three-microphone directional array with a single omnidirectional microelectromechanical systems microphone using a 6.25-kHz sampling rate.[9]

For agent localization, we added extra sensors to the backpack to supplement the received signal strength indicator (RSSI) inherent within the ZigBee-enabled SoC. These sensors include a six-axis inertial measurement unit, a three-axis magnetometer, and a microphone–buzzer couple for acoustic time of flight measurements.

LOCALIZATION TECHNOLOGIES AND ALGORITHMS

Localizing an under-rubble survivor in absolute coordinates involves two subproblems: localizing the survivor relative to the biobot, and localizing the biobot in either an absolute or relative frame of reference.

To localize a survivor relative to a biobot, we employed an array of microphones capable of finding the direction of a signal's arrival. By comparing the sound's signal strength at the three microphones, we were able

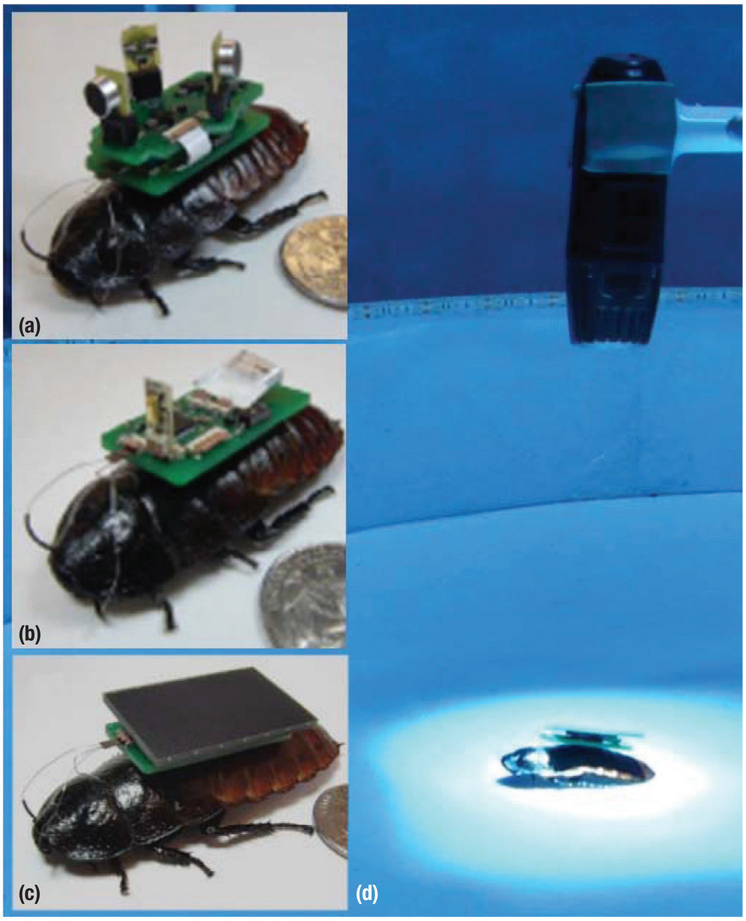

FIGURE 4. Miniaturized wireless electronic backpack developed for neurostimulation-based locomotion control, environmental sensing, localization of biobotic agents, and communication with first responders. (a) Unidirectional and (b) omnidirectional acoustic backpacks for sound localization. (c) Miniature solar cells were used to charge the backpack batteries by (d) interrupting the experiments.

to reliably establish the direction of a sound source.

The second part of the problem is localizing the biobots in the pile of rubble. GPS is unlikely to work because of signal attenuation through the rubble, as well as weight and power budgets. Our distributed solution relies on range measurements among neighboring biobots, and among biobots and fixed reference points (anchors) placed around the perimeter of the rubble pile (see Figure 6). We assume that the anchors can localize themselves in an absolute frame of reference using GPS or other methods; their main purpose in the system is to help localize the biobots in the rubble and to provide communication to those biobots. For range measurements, we focus on two technologies: RSSI and ultrasonic ranging.

RSSI is available in virtually every transceiver on the market today. This availability and its range—which is effectively the same as the communication range—make it a very attractive option. RSSI's main disadvantage is its inaccuracy; for Zigbee transceivers, indoor RSSI measurements might vary by as much as 20 dB while maintaining a fixed distance between the sender and receiver, even when having a line of sight.[10] Multipath fading is likely the main source of this variation. In rubble, we expect RSSI variability to be even higher.

Ultrasonic ranging involves measuring the propagation time of an ultrasonic signal from a transmitter to a receiver. To eliminate the need for network-wide synchronization, a packet can be transmitted to indicate to the receiver when the ultrasonic pulse was sent, thus allowing measurement of propagation time, which can be accurately translated to distance because of sound's relatively slow speed in air. The acoustic measurements rely on the biobots' buzzers and microphones. The main advantage of ultrasonic range measurements is their precision: submillimeter accuracy is possible. The main disadvantages are their range (especially under rubble) and their need for additional hardware, which entails additional weight and power consumption. Fortunately, the speakers and microphones can be reused for detecting and communicating with survivors.

The final challenge is devising a localization method that can provide the biobots' location given the range measurements. Although numerous papers have been published on localization in wireless sensor networks, their approaches are generally not appropriate for disaster conditions. To begin with, any approach relying on fingerprinting is excluded, because prior calibration is impossible in most disaster scenarios. Centralized approaches are also unsuitable, because the network might be loosely connected or even disconnected at times, and the biobots' mobility implies that the localization process must be repeated periodically. Furthermore, the extremely limited resources on the biobots means that approaches relying on significant amounts of communication or computation are also unsuitable. Thus, we are currently evaluating several fully distributed, low-computation localization

TABLE 1. System specifications for an ideal cockroach biobot backpack.

Subsystem	Requirements
Sensors	Miniature size (less than 1 × 1 cm^2)
	Low-power analog front end (less than 1 mW overall)
	On-board multichannel analog-to-digital converter
	I2C or serial peripheral interface support
	Sensor set: » Accelerometer (minimum three axes), gyroscope, magnetometer » Directional and omnidirectional microphones » Buzzer and speakers, light (ambient/infrared) » Gas detection (natural, petrochemicals, CO_2) » Optional camera and light sources (RGB, infrared)
Neurostimulation	Adjustable biphasic current stimulation (greater than 100 μA at 10 kohms, less than 100 ms, greater than 2 Hz)
	On-board tissue electrode interface analysis
	Locomotion control: » Forward, right/left turn, stop » Switching between active mode of exploration and static mode
CPU/MCU	Medium-level clock rate (greater than 16 MHz)
	Medium number of registers (greater than 32 × 8 bits)
	Sleep mode available
	Medium-level memory: flash greater than 128 Kbytes, RAM greater than 64 Kbytes, storage greater than 1,024 Kbytes
Communications	IEEE 802.15.4 support
	Peer-to-peer communication
	Directional and omnidirectional antennae
	High localization capability (less than 5 cm)
	10–100 mW transmitter range for biobots
	Greater than 100 mW power for base stations
	Audio frequency support (greater than 10 kHz)
	Receives signal strength indicator support
Power	High-capacity lithium polymer battery (greater than 200 mAh)
	Solar charging (when at surface) and directional radio frequency support
	Regulates voltage to support entire system
	Fast charging (less than 2 h)
	Multilevel duty cycled operation: sleep, search, audio transmit
Packaging	Water resistant
	Lightweight (less than 5 g)
	Miniature size (less than 2 × 5 cm^2)

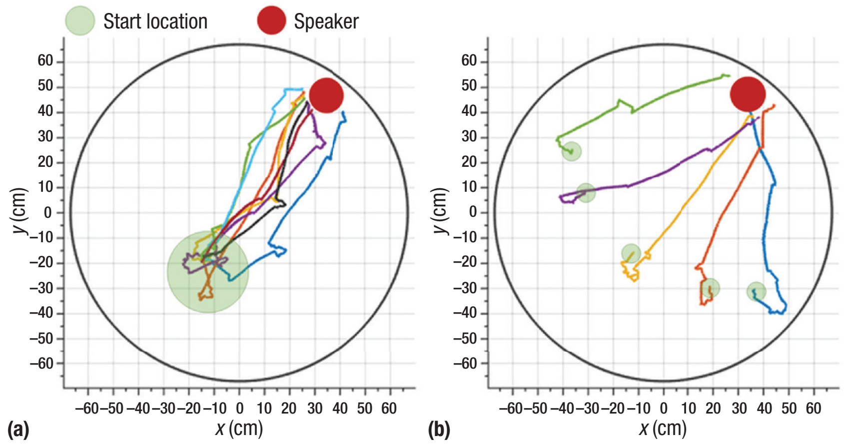

FIGURE 5. Sample trajectories as a result of automated steering with (a) varying orientations from the same start location and (b) varying start locations and an orientation away from the speaker. A miniature custom microphone array mounted on the biobots' backpacks allows detection and localization of sound sources. A video demonstrating a biobot trial can be found online at http://youtu.be/oJXEPcv-FMw.

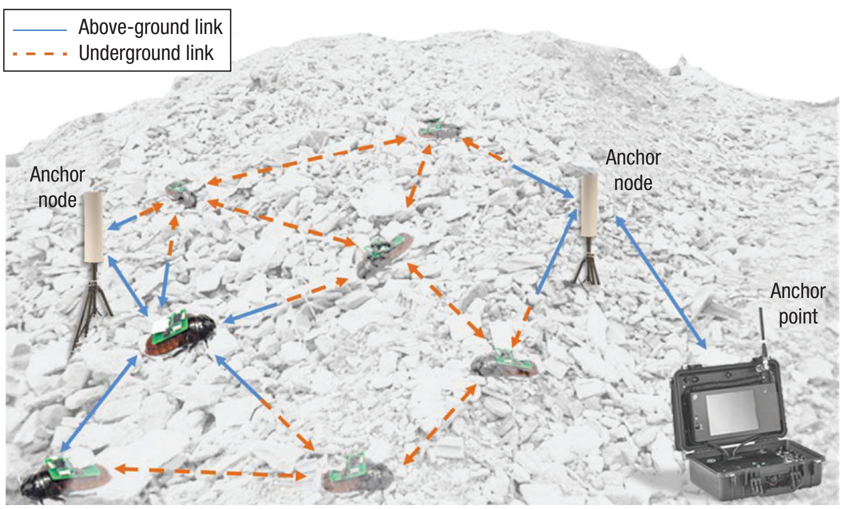

FIGURE 6. Localization and communication system that relies on anchor nodes on the surface and on range measurements among biobots above and below rubble.

approaches that are resilient to range measurement errors. Errors in range measurements will inevitably result in inaccurate localization; fortunately, tens of centimeters of error appear tolerable for our application.

MAPPING AND EXPLORATION STRATEGIES

One of the biobotic swarm's essential tasks is to create a map of the environment indicating which areas have been explored and the location of individuals requiring assistance. This task becomes extremely challenging in disaster scenarios because of hardware limitations, such as energy, locomotion, and communication bandwidth limitations, and the unstructured nature of the environment. Power and computational resource constraints prohibit us from using continuous control schemes for the agents' locomotion and from using onboard imaging techniques for their localization. Furthermore, because the location could be indoors or even underground in cluttered environments, signal propagation–based localization (such as GPS, signal strength computation, or time of flight) might be unreliable, and odometry information might include a high amount of uncertainty due to irregular terrain conditions. Therefore, traditional mapping and exploration techniques for simultaneous localization and mapping will not perform well under these adverse conditions.

Because obtaining an accurate metric map of the environment might not be possible in disaster scenarios, we are interested in constructing topological maps of unknown environments using biobotic mobile sensor networks under the constraint of limited sensing information. Our approach is to extract a sketch of the environment rather than a fully detailed map. This sketch includes robust topological information obtained from a minimal amount of sensing.[11] Instead of providing continuous control feedback to the agents, we explore how the insects' natural behavior, modeled using stochastic motion, and weak encounter information in the form of identification of nearby agents can be exploited for mapping. These strategies make up for our platforms' hardware limitations. Employing tools from algebraic topology, we can extract spatial information about the environment based on neighbor-to-neighbor interactions among the agents—with no need for localization data. We can then use this information to build a map of the environment's persistent and robust topological features.

Our topological mapping approach assumes no information about the agents' location. Instead, only encounters between nearby agents are recorded, together with the involved agents' unique IDs and the time at which the event occurred (see Figure

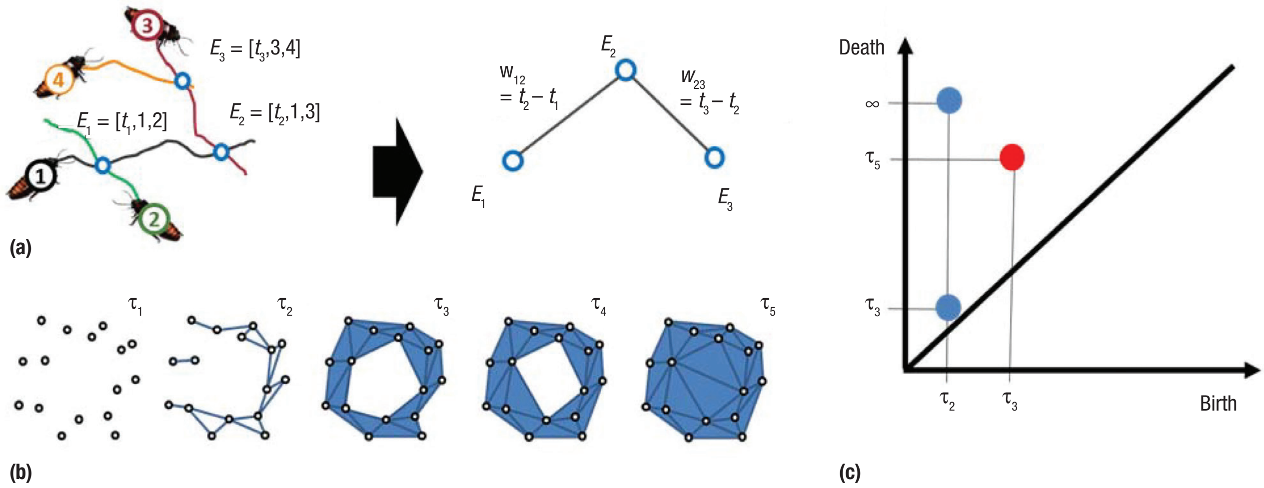

FIGURE 7. Topological feature extraction. (a) Constructing a graphical structure from encounters E_k among agents. Each encounter is represented as the tuple $E_k = [t_k, ID_1, ID_2]$, where t_k is the time of the event, and ID_1 and ID_2 are the identification numbers for the agents. (b) Filtration diagram illustrating the addition of edges between encounter events as a threshold τ, applied to the edge weights w, is increased. (c) Extracting persistent topological features from the encounter graph. Blue points indicate the birth and death of connected component features as a function of the threshold τ, and red points are associated with cycles in the space. Points farther away from the diagonal survive for a longer range of values and, hence, are more robust.

7). The encounter information is used to construct a graphical structure that captures approximate metric information about the environment and to extract robust topological features (such as the number of connected components and holes in the space) from the environment.[12] Robustness is quantified using persistence diagrams that capture the birth and death of topological features. We have validated this approach using simulation as well as real robotic platforms. This simple characterization of the space can become a building block for mapping larger environments. Figure 8 illustrates a scenario in which a drone is used as a leader for a biobot swarm. Local topological characterizations can be stitched together to build a global map of the scene. This representation provides a skeleton that can be used by more traditional localization and mapping schemes if other reliable sensing modalities become available.

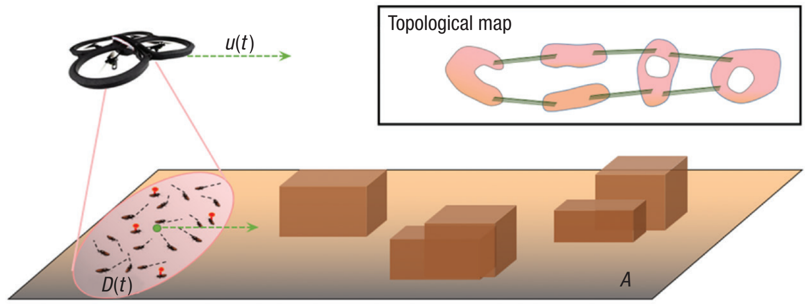

FIGURE 8. Topological mapping procedure using a swarm of guided biobot agents. A drone moving with velocity $u(t)$ is used as the leader. Robust topological features are extracted locally and stitched together to construct a more accurate map of the scene. Region A is the area of interest to be mapped. Region $D(t)$ is the area covered by the swarm at time t.

The CINEMa project has the potential to provide the infrastructure for a robust, flexible, mass-producible, and self-sustaining mobile sensor network for reconnaissance and survivor localization. Moreover, it provides a test bed for understanding the interfaces formed with insects by modeling individual and collective responses to various stimuli for further cyber-physical biobotic applications. The technologies and algorithms developed for search-and-rescue biobots, as well as the new findings on insect locomotory biology, can be applied to future centimeter-scale synthetic robotic swarms that physically and behaviorally mimic insects. ◼

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ABOUT THE AUTHORS

ALPER BOZKURT is an assistant professor in the Department of Electrical and Computer Engineering at North Carolina State University. His research interests include microsystem development for human–, animal–, and plant–machine interfaces and the Internet of bionic things. Bozkurt received a PhD in electrical and computer engineering from Cornell University and an MS in biomedical engineering from Drexel University. He is a member of IEEE, the IEEE Engineering in Medicine and Biology Society, Tau Beta Pi, and Sigma Xi. Contact him at aybozkur@ncsu.edu.

EDGAR LOBATON is an assistant professor in the Department of Electrical and Computer Engineering at North Carolina State University. His research interests include pattern recognition, robotics, and computer vision. Lobaton received a PhD in electrical engineering and computer science from the University of California, Berkeley. He is a member of IEEE, Tau Beta Pi, and the Society for Advancement of Chicanos/Hispanics and Native Americans in Science. Contact him at edgar.lobaton@ncsu.edu.

MIHAIL L. SICHITIU is a professor in the Department of Electrical and Computer Engineering at North Carolina State University. His research interests include wireless networking and multihop networks, particularly problems related to localization, time synchronization, routing, fairness, and mobility modeling and support. Sichitiu received a PhD in electrical engineering from the University of Notre Dame. He is a member of IEEE. Contact him at mlsichit@ncsu.edu.