MICROROBOTS

Integrating chemical fuels and artificial muscles for untethered microrobots

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Continued development of untethered insect-scale robots will require codesigned power and actuation strategies.

Microrobots could be used to navigate tight spaces that are inaccessible to people or traditional mobile robots for applications such as critical infrastructure inspection or search and rescue after natural disasters. These robots could also assist in ecological stewardship through artificial pollination or environmental monitoring. However, the vision of microrobots solving such societal and global challenges remains unrealized because of the difficulties in achieving practical power, actuation, and control capabilities at the insect scale (*1*). Writing in *Science Robotics,* Yang *et al.* introduce an integrated power and actuation approach for designing autonomous, insect-scale robots. They present RoBeetle, an 88-mg machine that uses a fuel-powered, catalytically active artificial muscle to achieve untethered operation (*2*).

Roboticists have introduced numerous strategies for microrobotic power, actuation, and control. Many microrobots require tethers to off-board power and control hardware, whereas others are powered by external electric or magnetic fields or light. There is also substantial interest in constructing microrobots from stimuli-responsive materials that change shape in response to variations in environmental conditions like temperature or relative humidity (*1*). Achieving truly untethered systems, however, requires that all power and control components be brought on-board (Fig. 1).

Batteries are commonly used in untethered microrobots because of their ubiquity and straightforward integration with embedded circuits for control and electrically driven actuators. For example, miniature lithium-ion batteries have been used to power untethered microrobots that move via micromotors (*3*) and piezoelectric actuators (*4*). However, batteries are limited in their ability to sufficiently supply energy for certain microrobot abilities and scales: Untethered microrobot flight, which requires high power density actuation and minimal body weight, was recently achieved by replacing heavy batteries with lightweight photovoltaic cells for on-board power generation (*5*), and tiny capacitors have powered some of the smallest, untethered microrobots to date (*6*). Moreover, building microrobots introduces materials and fabrication challenges that complicate battery and actuator design. Conventional motors are often replaced by piezoelectric actuators (*4*, *5*), dielectric elastomer actuators (*7*), and ionic electromechanically active polymers (*8*) that are easier to miniaturize, but not without their respective design and operational constraints.

Yang *et al.* achieve untethered operation in RoBeetle with a catalytically active shape memory alloy (SMA) wire that they engineered to be powered by the combustion of methanol. This approach is a codesigned power and actuation strategy that draws inspiration from living organisms, which are fueled by the metabolism of biochemicals like glucose and fat that have specific energies around 15 and 38 MJ/kg, respectively. At about 20 MJ/kg, the specific energy of RoBeetle's methanol supply is about 10 times higher than that of the best miniature batteries for microrobots. Methanol exothermically produces carbon dioxide and water vapor in the presence of oxygen and a catalyst like the platinum that coats the SMA wire in RoBeetle. SMAs are well-known high power density actuators that contract like biological muscle when heated. The heat generated from the methanol combusting in the presence of the SMA wire is sufficient to drive its contraction (*2*).

Chemical fuels are difficult to work with and store in microrobots, but they have been recently used in two soft-bodied robots to achieve untethered operation (*9*, *10*). Octobot used the catalytic decomposition of hydrogen peroxide into pressurized gas to power pneumatic actuation in an entirely soft machine free of hard components. A microfluidic device embedded in Octobot served as a soft controller that autonomously routed the liquid fuel to catalysts within Octobot's body, where gases produced inflated downstream actuator networks. This fluidically integrated power, actuation, and control approach enabled Octobot to alternate between actuation states in an untethered fashion (*9*). More recently, another fluidically integrated power and actuation scheme was introduced in an untethered robotic fish that used a multifunctional liquid catholyte as both the components of an on-board redox flow battery and the working fluid for hydraulic actuation (*10*). As RoBeetle and these two robots highlight, the use of chemical fuels in robots requires a careful codesign of a power-actuation strategy that synergistically couples energy release with driving the desired actuation. In other words, the power and actuation approaches in these systems do not work in isolation and must be engineered together to achieve autonomous operation.

Lastly, actuation has to be controlled so the microrobot can serve a useful, programmed function. Untethered microrobots can make use of on-board electronic circuitry if they can bear the payload. However, smaller robots must forgo these components and make shrewd use of their physical bodies to control actuation instead. Octobot achieved this through its soft, microfluidic logic-based controller (*9*). RoBeetle uses an analogous control strategy through a mechanical control mechanism that reduces methanol exposure to the SMA wire when it is contracted. This mechanical, morphological controller enables RoBeetle's legs to propel it forward through anisotropic friction (*2*).

Although RoBeetle is an exciting microrobotics milestone, there are opportunities for improvement. RoBeetle moves much more

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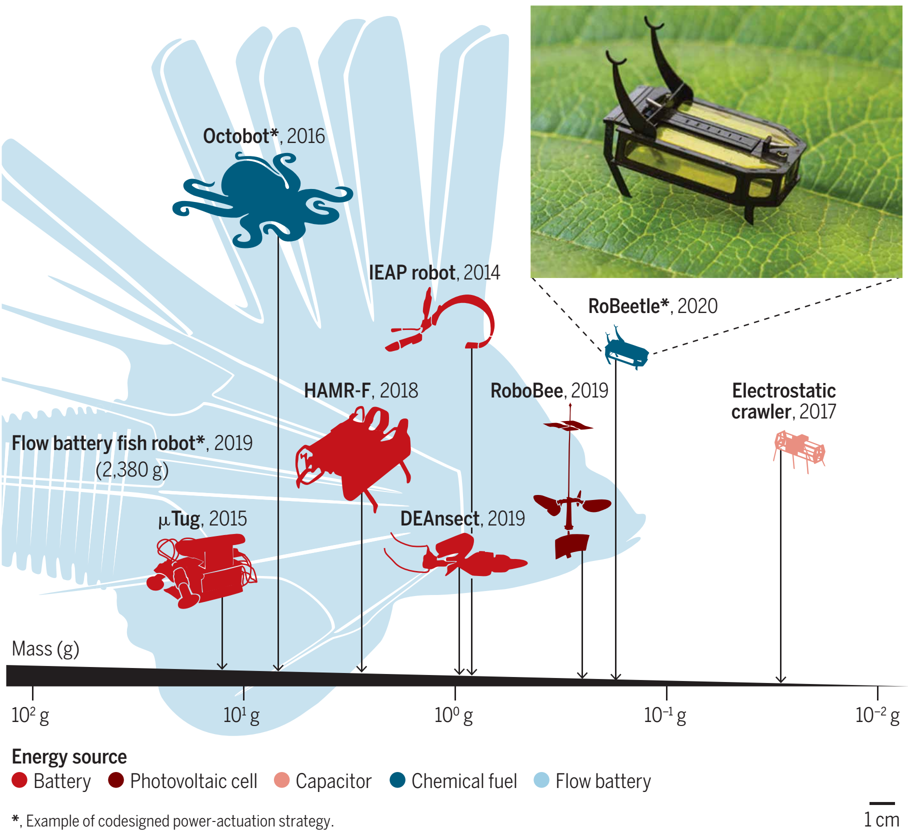

Fig. 1. Progress in untethered microrobots. Scaled silhouettes of untethered microrobots and bioinspired soft robots using different power and actuation strategies are shown to provide a size and weight comparison (scale bar, about 1 cm). Silhouette colors indicate how each robot is powered. The mass indicated includes the mass of the energy source; for a chemical fuel, this means the mass of a full on-board supply. From left to right, the robots are (with actuation strategy indicated in square brackets) as follows: a flow battery fish robot [hydraulic actuators, (10)], µTug [micromotors, (3)], Octobot [pneumatic actuators, (9)], HAMR-F [piezoelectric actuators, (4)], DEAnsect [dielectric elastomer actuators, (7)], an ionic electromechanically active polymer–driven robot [IEAP actuator, (8)], RoboBee [piezoelectric actuators (5)], RoBeetle [catalytically active shape-memory alloy, (2)], and an electrostatic crawler [electrostatic actuation, (6)].

slowly than other microrobots at 0.76 mm/s or 0.05 body lengths per second. The robot is also limited to continuous forward motion; controlled steering, speed, or multi–degree-of-freedom actuation are not possible. Lastly, forgoing traditional electronic controllers in place of mechanical or morphological ones inherently reduces the sophistication of RoBeetle's capabilities, complicates paths to advanced behaviors, and restricts opportunities for external control or communication (*2*).

Continued progress in microrobots and similar untethered robots will require advances in codesigned power-actuation capabilities. New fuels and actuators, as well as concomitant advances in microrobotics fabrication, will enable more complex behaviors, such as jumping or multimodal locomotion. These efforts will need to be accompanied by continued work in the design of morphological controllers to enable more sophisticated functions and practical utility.

Other critical challenges to address include how to refuel chemically powered robots for long-term, continuous operation and how to program or communicate with them for certain tasks. Interdisciplinary efforts are expected to provide solutions to these exciting research challenges, ensuring the field moves ever closer toward truly autonomous, insect-like robots.

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10.1126/scirobotics.abd7338

Citation: R. L. Truby, S. Li, Integrating chemical fuels and artificial muscles for untethered microrobots. *Sci. Robot.* **5**, eabd7338 (2020).

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Sci. Robot., 5 (45), eabd7338. • DOI: 10.1126/scirobotics.abd7338

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