Challenges for Effective Millirobots

Ronald S. Fearing
Dept. of Electrical Engineering and Computer Sciences
University of California
Berkeley, CA 94720-1770

Abstract— **Centimeter-scale robots will create the opportunity to manipulate, sense and explore a wide range of environments with greatly reduced cost and expanded capabilities. In many applications, the capability of millirobots depends on mobility, multiplicity, and intelligence. For intelligence, sensing and computation capabilities are now almost available off the shelf. However, there are significant challenges for millirobots in creating all-terrain capable mobility, and low production costs for multiplicity. The mesoscopic range between MEMS and conventional robots provides a new domain with rich challenges. There are advantages to this size scale for novel low-cost fabrication methods, including rapid prototyping of millirobots from kits of parts. This paper provides an overview of some approaches to key challenges in millirobots for design, fabrication, actuation, and power, illustrated by examples in legged and winged millirobots made using carbon fiber.**

I. INTRODUCTION

In the future, millirobots in the range of 0.1 to 10 grams will be capable of performing useful tasks such as search and rescue, and carrying useful payloads (such as "Smart Dust" [8]). For mobility, both flight and legged locomotion are appropriate. At smaller scales, silicon-based fabrication techniques have been used for miniature walking robots [5], [6], [18]. However, there are difficulties with scaling silicon processes up to larger sizes, as well as scaling conventional mechanisms down in size. This paper discusses some of the fabrication technology which can be used to build millirobots in this size range, and then discusses some example designs from the author's research group. The power density and efficiency considerations for millirobots are as severe as for macrorobots, and efficient drive methods are necessary.

II. MOTIVATION FOR MILLIROBOTS

As a motivating example for millirobots, consider the problem of finding survivors in a collapsed building, for which a simplified example is shown in Fig. 1, 2. In a collapsed building, it is reasonable to assume that there will be many narrow passages which twist and turn and dead end. We assume that due to their low cost (eventually $<$ \$10 each) hundreds of millirobots can be placed in promising openings, and their progress can be monitored from a safe distance. Due to limited battery life, a Brownian motion strategy for finding promising interior openings to explore will not be effective. To conserve battery life, a few millirobots should be actively exploring, while the majority are perched on idle, waiting for discovery of new "interesting" paths. When a sufficiently interesting path is found, a swarm of millirobots can be dispatched to enter the newly found space and repeat the process of exploration and mapping. Due to the low cost of the millirobots, mapped paths can be marked by a perched millirobot to provide position information and communication relay capability through the network back to the outside. Using acoustic sensors, survivors could be found if there is a path to them.

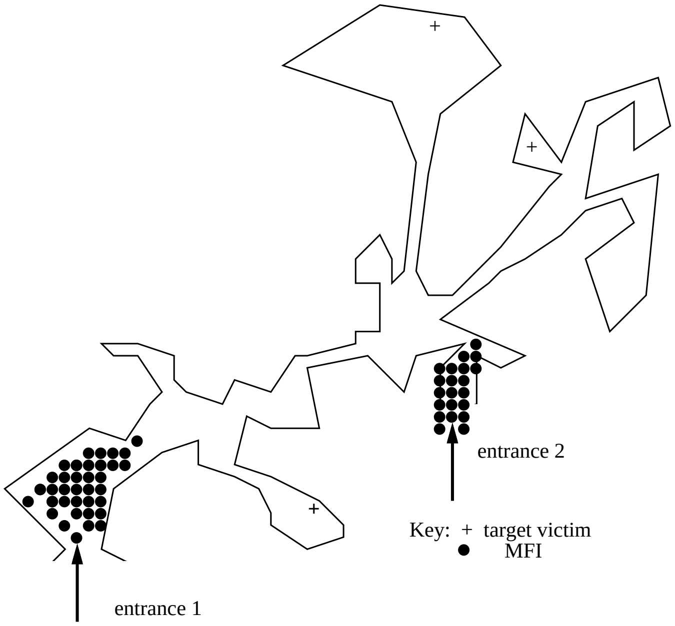

Fig. 1. Motivating example for millirobots, showing simplified 2D representation of example application for finding survivors in collapsed building, with initial position for mobile millirobots.

To qualitatively assess the capability of a network of mobile millirobots, the following relation can be posed:

$$\text{Capability} = \text{Multiplicity} \cdot \text{Mobility} \cdot \text{Intelligence}. \quad (1)$$

Multiplicity is simply the number of units. A larger number of units provides redundant communication pathways, and wider area search coverage. Intelligence includes sensing, communication and decision making. Mobility rates the ability to locomote, for example the distance which can be traveled. In a rubble environment, a millirobot with wheels might have a mobility of 1.0, while a gecko-inspired climbing millirobot or flying millirobot might have a mobility of 10.

The communications relay problem provides a concrete example of the advantages of multiplicity in mobile millirobots. Consider a pair of millirobots with a communications

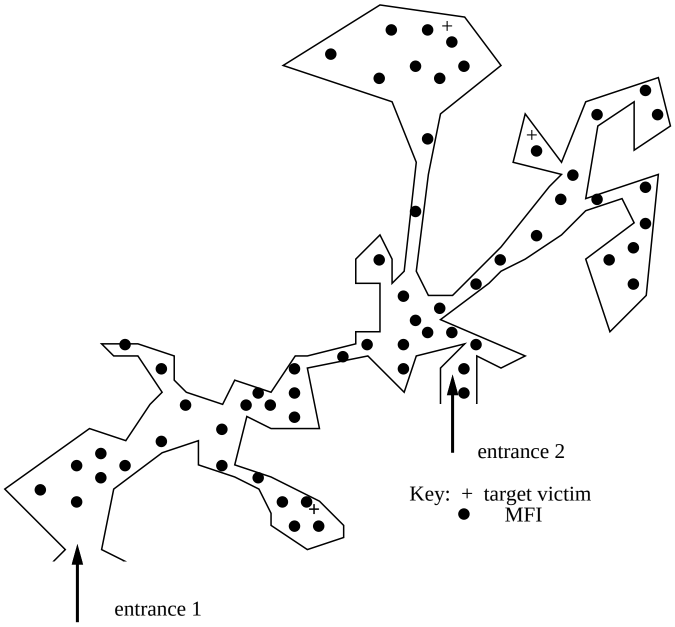

Fig. 2. Millirobots cooperatively explore using joint sensing and communication to efficiently find survivors in debris and notify rescuers outside building.

channel in free space which requires 100 mW for 250 kbps at $r_1 = 2000m$. Consider using a battery with energy density of $100J \cdot gm^{-1}$, then a pair of 10 gram millirobots will be able to maintain communication for 10^4 sec. Now for $r_2 = 500m$, only 6 mW will be required. Using a relay system, 5 millirobots would be required, each with a battery mass of 0.6 grams. Hence a reduction in total battery mass from 20 grams to 3 grams is possible by using more, smaller millirobots. It is interesting to note that mobility also has a big effect on UHF communications capacity as multipath attenuation effects could be reduced by moving away from signal stength nulls.

III. FABRICATION AND ASSEMBLY

For aerial and terrestrial millirobots in the size range from 0.1 grams to 10 grams, conventional fabrication and design methods are inadequate. High friction, high weight, low durability, and high cost limit construction techniques using precision machinery such as ball-bearings, gears, and cams. Flexure-based mechanisms [7] such as Shape Deposition Manufacture [3] and laser-cut composite-flexure laminates [14] provide a means to fabricate low-loss millirobot structures. As shown in Figure 3, two carbon fiber layers with an intermediate flexure layer can form links and joints, with typical joint limits of $\pm 60^{\circ}$.

As an example of the capabilities of the process, consider the Micromechanical Flying Insect (MFI) thorax shown in Figure 6. Each wing is driven by two piezoelectric actuators at 200 Hz through a compound 4-bar mechanical amplifier with gain of $3200rad \cdot m^-1$. The two actuators are coupled by a differential to give control over wing flapping and rotation angle. Each wing has 15 flexure joints for two degrees of freedom. The components for the MFI thorax are shown in Figure 4.

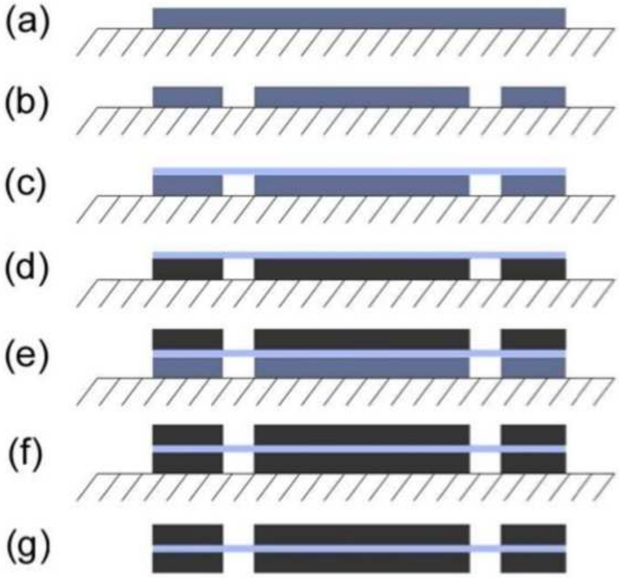

Fig. 3. Process for making links and flexure joints using laser micromachining. a) Carbon fiber layer 1. b) Flexure cuts. c) Stack polyester flexure layer. d) Cure carbon fiber to flexure layer. e) Stack cured carbon fiber layer on uncured layer 2. f) Cure both layers. g) Remove parts from substrate.

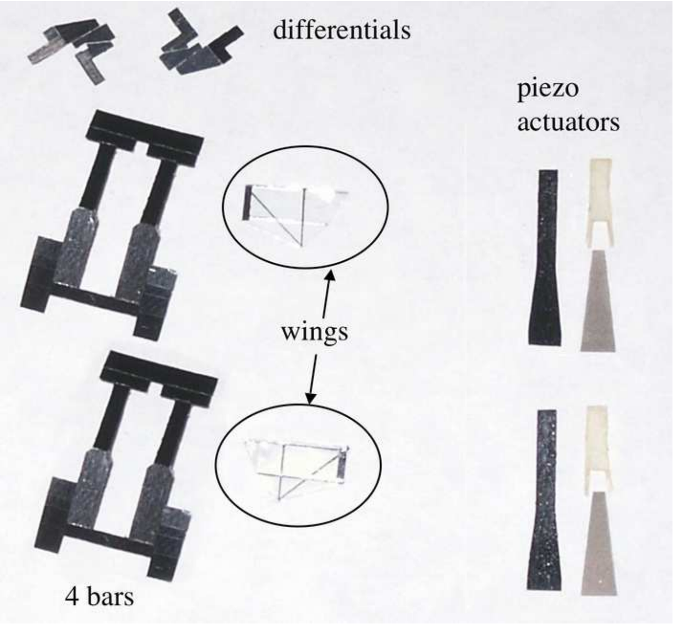

Fig. 4. Laser-cut components for MFI thorax.

While joints and links can be laser-micromachined, integration of other components such as sensors, actuators, and electronics still requires assembly. For flexibility in fabrication, link and joint module kits can be created [10]. Using parameterized link lengths, carbon fiber millirobots could be specified using microassembly from pallets of precut components

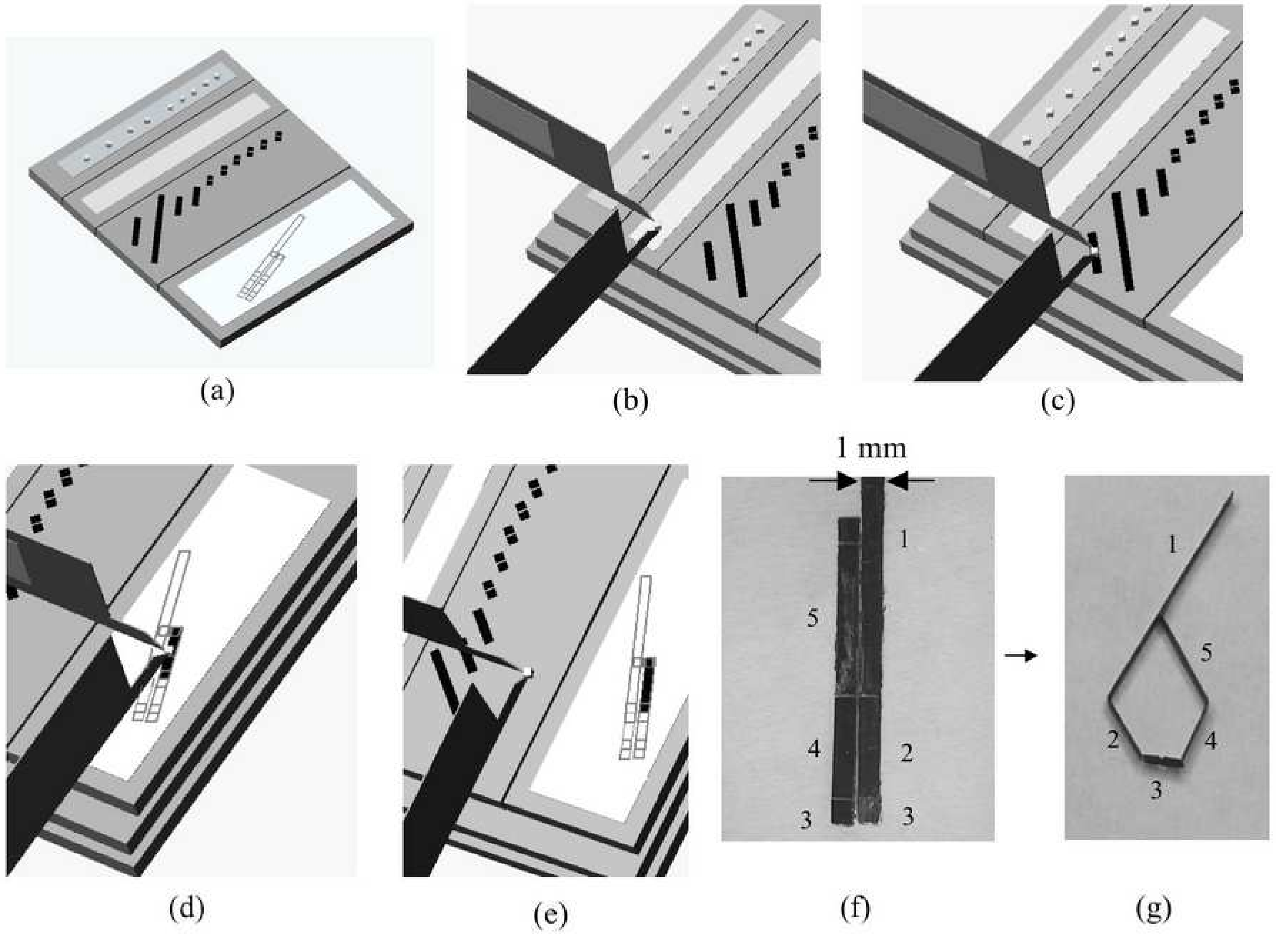

Fig. 5. CAD model of the Ortho-tweezers assembling millirobot parts. (a) A pallet is assembled with the needed parts, and placed on a substrate with controllable heaters. (b) The Ortho-tweezers picks up a handling block and dips it in low-melting point wax. (c) The handling block is attached to a part, for example a link. (d) The handling block and part combination is reoriented and the part is put in place, in this example, for a 5 bar linkage. (e) The handling block is returned to the pallet. (f) Assembled five-bar (unfolded). (g) Assembled five-bar linkage, after folding.

(Figure 5). To simplify the microassembly task, a rectangular handling block can be used to standardize manipulation of all parts, including large flat plates which are otherwise difficult to handle.

IV. MILLIROBOT DESIGN

The carbon fiber fabrication technology has been used in several millirobot projects, including the Micromechanical Flying Insect (MFI) (Figure 6), a 2.5 gram glider (Figure 7), and a 3.5 gram prototype crawling robot (Figure 8). To date, the MFI (using benchtop power) has achieved lift from a single wing of $> 500\mu N$ which is just below what is needed for takeoff [1]. Further structural improvements to increase wing beat frequency and amplitude will be needed for first flight.

For wide area coverage, a glider has much longer range and lower power requirements than a flapping flyer. We constructed a minimal control glider using two elevon control surfaces driven by piezoelectric actuators [15]. As for all mobile millirobots, the battery determines minimum size, in this case using a 700 milligram Kokam battery resulted in a final weight of 2.5 grams, including on-board PIC controller and DC-DC boost converter to drive the piezoelectric actuators. The glider has shown basic autonomous flight, including turning towards an IR light source.

For millirobots to traverse rough terrain, conventional sensor and model-based foot placement algorithms will be too slow and error prone. Instead, the robot structure needs to have a high power-to-weight ratio, and use tuned compliance with passive stability to locomote [12]. We have begun design of a lightweight low DOF hexapod robot using carbon fiber structure and just two piezoelectric actuators (Figure 8) [11]. For small, light weight robots, we plan to use biologically inspired fibrillar adhesives to give all-terrain climbing ability. With a predicted adhesion of $10mN \cdot mm^{-2}$, only a few square millimeters of material would be required to support a 35 mN crawler. Microfiber arrays such as shown in Figure 9 [9] can also provide very high friction needed for traction on smooth surfaces. (We plan to integrate these fiber arrays with the crawler testbed in the near future.)

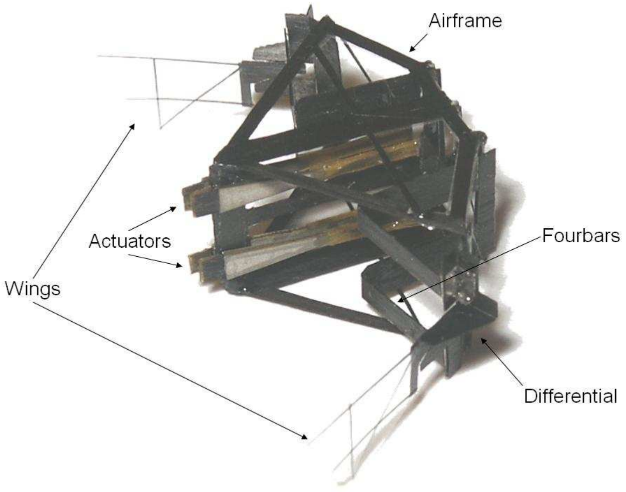

Fig. 6. Micromechanical Flying Insect (MFI) with airframe, actuators, transmission and wings with mass of 0.13 gram.

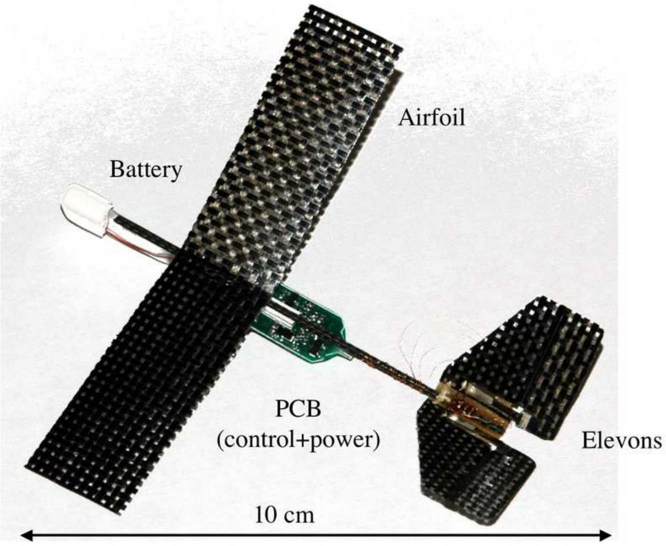

Fig. 7. 2.5 gram autonomous glider.

V. POWER CONSIDERATIONS

High performance mobility requires high delivered mechanical power. For wall climbing at say $1m \cdot sec^{-1}$, perfect climbing (such as winding a rope around a pulley) requires a minimum of 10 W/kg. Using birds and insects as an example model, hovering flapping flight requires approximately 100 W/kg [13]. The high inertial loads of flapping and running require resonant drive systems [2]. A key challenge is appropriate impedance matching, so that actuators can operate close to their optimum power density point.

Insect flight muscle provides 200-400 Wkg^{-1}. The smallest commercially available actuator (Faulhaber 70 mg DC motor) would consume almost the entire MFI mass budget for a single motor. We thus developed our own custom actuators, based on multilayer piezoelectric bending actuators [17], [16]. The actuators shown in Figure 10 consist of 2 layers of PZT with an intermediate carbon fiber layer, and can provide $\approx 200Wkg^{-1}$ at a field of $2{\times}10^6 Vm^{-1}$. The reason for the high performance is by creating a more uniform bending moment throughout the actuator material, increasing the average strain energy density. This is done by combining a triangular plate with a rigid extension. In addition, we use laser cutting to reduce cracks at the edges.

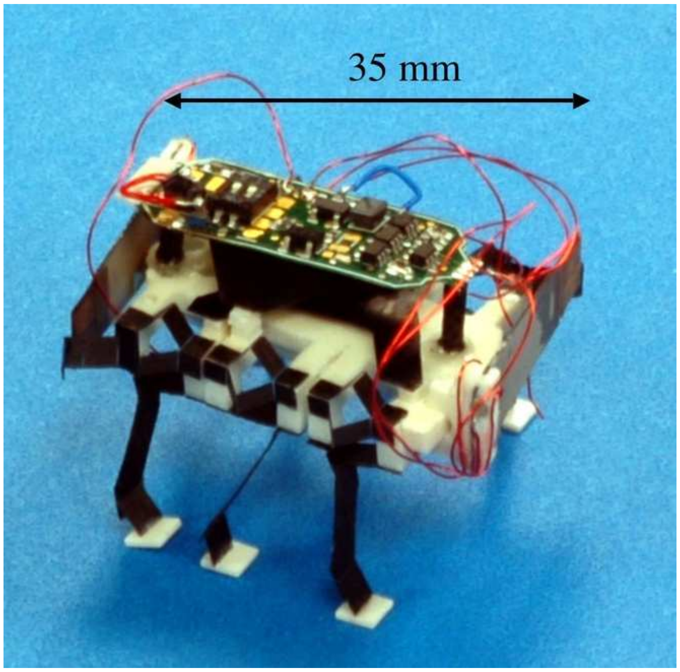

Fig. 8. Integrated crawler testbed.

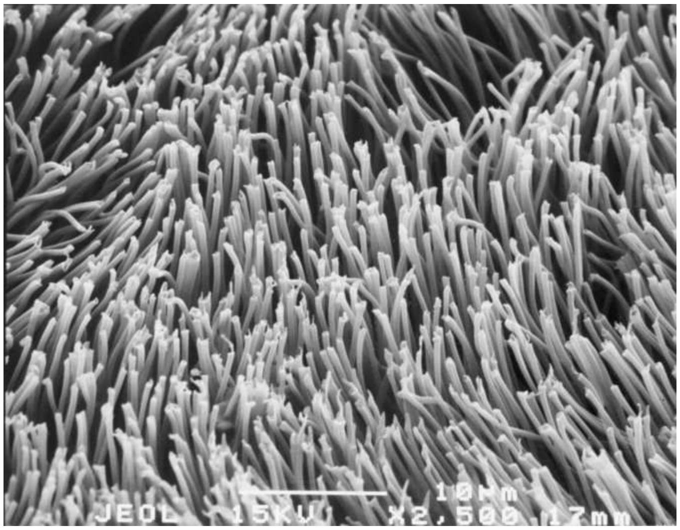

Fig. 9. SEM of an array of 20 μm long, 0.6 μm diameter polyimide fibers etched from a polycarbonate membrane; scale bar represents 10 μm.

Efficient power conversion and transmission is particularly important for millirobot flapping flight, where actuators and batteries are barely adequate. An example end-to-end power

Fig. 10. Piezoelectric bimorph actuator for MFI.

accounting for the MFI is shown in Figure 11. Flexure-based thoraxes such as for the MFI have efficiencies of approximately 90%. The biggest concern in the design, after the battery (which does not yet exist), are the large internal losses in the PZT, and the small coupling factor between stored electrical and mechanical energy in the bimorph configuration. To reduce the electrical losses, charge recovery circuits such as [4] will be required.

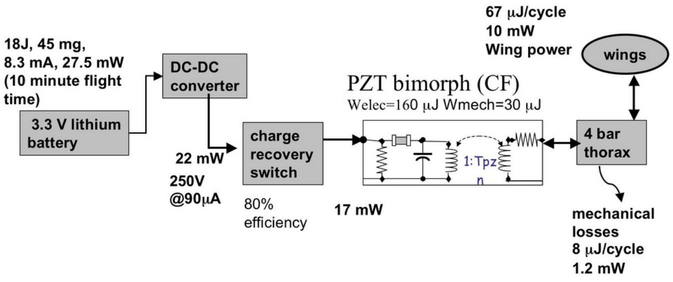

Fig. 11. Overall power and energy budget for free flight of MFI.

VI. CONCLUSION

This paper showed how some of the challenges to creating effective mobile millirobots are being addressed, particularly in rapid prototyping of high speed structures using carbon fiber flexure technology. Even with this technology, achieving high power densities, particularly with off-the-shelf batteries, is still difficult, and requires careful attention to joint and structure design. For millirobots, high mobility can be addressed using flight and crawling modes. With laser micromachining and microasembly, it should be possible to implement large numbers of millirobots cheaply (high multiplicity). An extremely interesting challenge in the next few years is to determine how to achieve high capability for a whole network without requiring high intelligence in each individual millirobot.

ACKNOWLEDGMENT

The author would like to thank the members of the Biomimetic Millisystems Lab and our sponsors over the last 8 years including National Science Foundation, Office of Naval Research, and DARPA.

REFERENCES

[1] S. Avadhanula, R. J. Wood, E. Steltz, J. Yan and R. S. Fearing "Lift Force Improvements for the Micromechanical Flying Insect" *IEEE Int. Conf. on Intelligent Robots and Systems,* Oct 28-30, 2003, Las Vegas NV.

[2] S. Avadhanula, R.J. Wood, D. Campolo, and R.S. Fearing. Dynamically tuned design of the MFI thorax. In *IEEE Int. Conf. on Robotics and Automation*, Washington, DC, May 2002.

[3] S.A. Bailey, J.G. Cham, M.R. Cutkosky, and R.J. Full, "Biomimetic Robotic Mechanisms via Shape Deposition Manufacturing," *Robotics Research: The Ninth International Symposium,* J. Hollerbach and D. Koditschek, Eds. London: Springer-Verlag, 2000, pp. 403-410.

[4] D. Campolo, M. Sitti, and R.S. Fearing, "Efficient Charge Recovery Method for Driving Piezoelectric Actuators in Low Power Applications," *IEEE Trans. on Ultrasonics, Ferroelectrics and Frequency Control,* vol. 50, no.3, pp. 237-244, Mar. 2003.

[5] T. Ebefors, J.U. Mattsson, E. Kalvesten, and G. Stemme, "A walking silicon micro-robot," *10th Intl. Conf. on Solid-State Sensors and Actuators,* Sendai, Japan, pp. 1202-1205, June 1999.

[6] S. Hollar, A. Flynn, C. Bellew, K.S.J. Pister, "Solar powered 10mg silicon robot," *MEMS 2003,* Kyoto, Japan, Jan. 2003.

[7] L.L. Howell, *Compliant Mechanisms,* Wiley, New York 2001.

[8] J. M. Kahn, R. H. Katz, K. S. J. Pister, "Emerging Challenges: Mobile Networking for Smart Dust," *Journal of Communications and Networks,* vol. 2, no. 3, pp. 188-196, September 2000.

[9] C. Majidi, R.E. Groff, K. Autumn, S. Baek, B.Bush, N. Gravish, R. Maboudian, Y. Maeno, B. Schubert, M. Wilkinson, and R.S. Fearing, "High friction from a stiff polymer using micro-fiber arrays," *Physical Review Letters,* vol. 97, no. 076103, 18 August 2006.

[10] R. Sahai, E. Steltz, and R.S. Fearing, "Carbon Fiber Components with Integrated Wiring for Millirobot Prototyping," *IEEE Int. Conf. on Robotics and Automation,* Barcelona, April 2005.

[11] R. Sahai, R.E. Groff, E. Steltz, M. Seeman, and R.S. Fearing, "Towards a 3g Crawling Robot through the Integration of Microrobot Technologies," *IEEE Int. Conf. on Robotics and Automation*, Orlando, FL May 15-19, 2006.

[12] U. Saranli, M. Buehler, and D.E. Koditschek, "RHex: a simple and highly mobile hexapod robot," *Intl. J. of Robotics Research,* vol. 20, pp. 616-631, July 2001.

[13] E. Steltz, M. Seeman, S. Avadhanula, and R.S. Fearing,"Power Electronics Design Choice for Piezoelectric Microrobots" *IEEE Int. Conf. On Robotics and Intelligent Systems,* Beijing Oct. 9-15, 2006.

[14] R.J. Wood, S. Avadhanula, M. Menon, and R.S. Fearing. Microrobotics using composite materials: The micromechanical flying insect thorax. In *IEEE Int. Conf. on Robotics and Automation*, Taipei, Taiwan, September 2003.

[15] R.J. Wood, S. Avadhanula, E. Steltz, M. Seeman, J. Entwistle, A. Bachrach, G. Barrows, S. Sanders, and R.S. Fearing. Design, fabrication and initial results of a 2g autonomous glider. In *Conf. of IEEE Industrial Electronics Society*, Raleigh, NC, November 2005.

[16] R.J. Wood, E. Steltz, and R.S. Fearing. Nonlinear performance limits for high energy density piezoelectric bending actuators. In *IEEE Int. Conf. on Robotics and Automation*, Barcelona, Spain, April 2005.

[17] R.J. Wood, E. Steltz, and R.S. Fearing. Optimal energy density piezoelectric bending actuators. *J. of Sensors and Actuators A: Physical*, 119(2):476–488, 2005.

[18] R. Yeh, S. Hollar, and K.S.J. Pister, "Design of low-power silicon articulated microrobots," *Journal of Micromechatronics,* vol. 1, no. 3, pp. 191-203, 2002.