

SAWYER BUCKMINSTER FULLER

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Research Interests

Achieving autonomous control of insect-scale robots, particularly flying robots, so they can perform useful tasks. As scale diminishes, different physical effects begin to dominate, requiring new technology for many components, from actuators to sensing to control algorithms. Through a combination of forward-engineering at-scale robot prototypes and reverse-engineering insect perception, control, and aeromechanics, I hope to find scale-compatible solutions. Areas of particular interest are in visual navigation, localizing sources of odor plumes, and the interplay of control and mechanics.

Education

- Ph.D. **California Institute of Technology (Caltech)**
Bioengineering, June 2011
Minors: Control and Dynamical Systems, Electrical Engineering
Thesis title: Steady as she goes: Visual autocorrelators and antenna-mediated airspeed feedback in the control of flight dynamics in fruit flies and robots
Advisors: Richard M. Murray and Michael H. Dickinson
- M.S. **Massachusetts Institute of Technology (MIT)**
Mechanical Engineering, June 2004
Advisors: H. Sebastian Seung and Shuguang Zhang
- B.S. **Massachusetts Institute of Technology**
Mechanical Engineering, June 2000
Advisor: Joseph M. Jacobson

Research

HARVARD UNIVERSITY Cambridge, MA
2011 – 2015
Postdoctoral Scholar. Flight control and sensor development for insect-sized flying robots. Advisor: Prof. Robert J. Wood. Organized subgroup of 7-10 graduate students and postdocs devoted to fabrication and control of these vehicles during Prof. Wood's sabbatical year.

CALIFORNIA INSTITUTE OF TECHNOLOGY Pasadena, CA
2004 – 2011

Graduate Research Assistant during Ph.D. Demonstrated a low-power, < 1 million operations per second (MFLOPS) visual motion controller on a fly-inspired robot. Characterized the the feedback responses and sensory fusion of vision and antenna-mediated wind sensing in flying *Drosophila*. Designed and built an air piston for wind stimulus and system of mirrors to apply projector-based visual stimulus. Wrote software to perform black-box system identification and statistical analysis of the fly's feedback regulator based on trajectories recorded by an array of cameras. Advisors: Profs. Richard Murray (Dept. of Control and Dynamical Systems) and Michael Dickinson (Dept. of Bioengineering).

UNIVERSITY OF VERONA
2003 – 2004

Verona, Italy

Designed and fabricated 6-axis strain gauge sensor hardware and a low-noise analog-to-digital converter for a robotic end-effector. Advisor: Prof. Paolo Fiorini.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
2001 – 2003

Cambridge, MA

Graduate Research Assistant during Master's degree. Built custom, high-resolution ink-jet printer to deposit patterns of neuron growth scaffolding materials. Neurons from the rat hippocampus grew onto patterns, formed synapses, and remained confined to patterns for up to a month exhibiting spiking activity. Advisors: Profs. H. Sebastian Seung (Brain and Cognitive Science), Shuguang Zhang (Bioengineering), and Joseph M. Jacobson (Media Laboratory).

NASA JET PROPULSION LABORATORY (JPL)
2000 – 2001

Pasadena, CA

Co-op Intern. Built the embedded wireless microcontroller for a frog-hopping planetary rover. Advisors: Profs. Paolo Fiorini of JPL and Joel Burdick of Caltech.

MIT MEDIA LABORATORY
1998 – 2000

Cambridge, MA

Undergraduate Research Assistant. Built and patented the first robotic printer capable of fabricating electric circuitry by ink-jet printing. Using nanoparticle ink, the printer could additionally fabricate three-dimensional micro-electromechanical (MEMS) actuators. Printed devices included a resonant inductive coil, electrothermal actuators, and an electrostatic motor. This patented technology was used to launch a startup to fabricate printed electronics, Kovio Inc., that has since ceased operations. Advisor: Prof. Joseph M. Jacobson.

Honors and Scholarships

National Science Foundation Graduate Fellowship

Caltech Bioengineering Graduate Fellowship

Stanford Materials Science Graduate Fellowship (declined)

MIT Presidential Fellow

MIT Mech. Eng. Dept. Fellowship (awarded to top $\frac{1}{4}$ of admitted students)

NASA Technical Award: "Hopping Robot with Wheels"

MIT Silent Hoist & Crane Award for Outstanding Undergraduate Thesis

2nd Place (of 144): MIT 2.007 Mech. Eng. Robot Design Contest
 Participant in NHK ROBOCON International Robot Contest, Tokyo Japan (nationally televised in Japan)
 Both “Fastest Ever” and voted “Best Looking” (of 75): MIT Stirling Engine contest

Teaching and Mentoring

Teaching Assistantships	
Caltech Biomechanics	Forces and flows in biology Instructor: Prof. Michael Dickinson
Caltech Feedback Control II	Robust control, optimal nonlinear control, Kalman Filter Instructor: Dr. Doug MacMartin
Caltech Feedback Control I	State-space and frequency-domain linear systems Instructor: Prof. Richard Murray * gave weekly recitation lecture
MIT Mech. Eng. Design	Formalized mechanism design, hands-on fabrication Instructor: Prof. Alex Slocum
MIT Auton. Lego Robotics	Student-organized course on autonomous robotics
Guest Lectures	
MIT Mol. Struc. of Biomat.	Molecular structure of proteins, bone, silk, etc. Instructor: Shuguang Zhang topic: Ink-jet fabricated bioscaffolds
MIT Make Anything “Fab”	Electronics, machining, prototyping Instructor: Neil Gershenfeld topic: Computer Numeric Controlled (CNC) mill
Mentoring	
undergraduates	primary mentor for 6 students 2 coauthored peer-reviewed conference articles 1 senior design thesis
graduate students	primary collaborator with 5 graduate students 3 coauthored peer-reviewed conference articles 1 journal article (<i>Science</i>)

Skills

I have designed the mechanics and mechanisms, sensor and electronics hardware, motor hardware, and feedback control systems for robots and actuators ranging in size from from 3 mm to 30 cm. Experienced with MATLAB (5 years) and Python (5 years, contributor to Python control systems package). I favor Python because it is open source and has more modern language features, plotting tools, and user interface (e.g. matplotlib and iPython notebook), but MATLAB has stronger realtime control integration (xPC Target). I also have experience with embedded microcontroller programming in C and assembly (6 months).

Interests

Frequent leader/instructor for outdoor excursions, e.g. camping and backpacking

with laboratory research groups. Trained more than 20 on basics of surfing, for example through “Learn to Surf” trips for the Caltech Surf Club. Graduate of 30-day National Outdoor Leadership School mountaineering course. Visual arts such as painting (won the “Art of Science” contest at Caltech in 2008).

Journal Articles

1. **S. B. Fuller**, M. Karpelson, A. Censi, K. Ma, and R. J. Wood, “Controlling free flight of a robotic fly using an onboard vision sensor inspired by insect ocelli,” *J. Royal Society Interface* (2014) Vol. 11 No. 97.
2. **S. B. Fuller**, A. Straw, M. Peek, R. Murray, and M. Dickinson, “Flying *Drosophila* stabilize their vision-based velocity controller by sensing wind with their antennae,” *Proc. Nat. Acad. Sci.* (2014) Vol. 111, No. 13, pp. E1182–E1191.
(top 10%, Altimetric attention score for same-age articles in *PNAS*)
3. K. Y. Ma, P. Chirarattananon, **S. B. Fuller**, and R. J. Wood, “Controlled flight of a biologically inspired, insect-scale robot,” *Science* (2013) Vol. 340, No. 6132, pp. 603–607.
(top 2%, Altimetric attention score for same-age articles in *Science*)
4. N. E. Sanjana and **S. B. Fuller** (Authors contributed equally), “A fast flexible ink-jet printing method for patterning dissociated neurons in culture,” *J. Neuroscience Methods* (2004) Vol. 136, pp. 151–163.
(Cited by 107 on ISI Web of Knowledge)
5. **S. B. Fuller**, E. J. Wilhelm, and J. M. Jacobson. “Ink-jet printed nanoparticle micro-electromechanical systems,” *IEEE/ASME J. Micro-electromechanical Systems* (2002) Vol. 11, No. 1, pp. 54–60.
(Cited by 267 on ISI Web of Knowledge)

Journal and Conference Articles Under Review

1. **S. B. Fuller** & Z. E. Teoh (authors contributed equally), P. Chirarattananon, N. O. Pérez-Arancibia, J. Greenberg, and R. J. Wood. “Stabilizing air dampers for insect-scale hovering aerial robots: An analysis of nonlinear dynamics based on flight tests gives design guidelines,” *Autonomous Robots*. (under review)

Peer-Reviewed Conference Articles

1. **S. B. Fuller**, J. P. Whitney, and R. J. Wood, “Rotating the heading angle of flapping-wing flyers by wriggle-steering,” *IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (Hamburg, Germany, September 2015).
2. E. F. Helbling, **S. B. Fuller**, and R. J. Wood, “Altitude Estimation and Control of an Insect-Scale Robot with an Onboard Proximity Sensor,” *International Symposium on Robotics Research (ISRR)* (Sestri Levante, Italy, September 2015)

3. D. Miller, I. Fitzner, **S. B. Fuller**, and S. Revzen, “Focused Modularity: Rapid Iteration of Design and Fabrication of a Meter-Scale Hexapedal Robot,” *Int. Conf. Climbing and Walking Robots (CLAWAR)* (Hangzhou, China, September, 2015).
4. **S. B. Fuller** & E. F. Helbling (authors contributed equally), P. Chirarattananon, and R. J. Wood, “Using gyroscope feedback to stabilize the attitude of a fly-sized hovering robot,” *Int. Conf. Micro Air Vehicles (IMAV)* (Delft, the Netherlands, August 2014). ([video link](#))
5. E. F. Helbling, **S. B. Fuller**, and R. J. Wood, “Pitch and yaw control of a robotic insect using an onboard magnetometer,” *IEEE Int. Conf. Robotics and Automation (ICRA)* (Hong Kong, May 2014).
6. **S. B. Fuller**, A. Sands, A. Haggerty, M. Karpelson, and R. J. Wood, “Estimating attitude and wind velocity using biomimetic sensors on a microrobotic bee,” *IEEE Int. Conf. Robotics and Automation (ICRA)* (Karlsruhe, Germany, May 2013).
7. Z. E. Teoh, **S. B. Fuller**, P. Chirarattananon, N. O. Pérez-Arancibia, J. Greenberg, and R. J. Wood, “A Hovering flapping-wing microrobot with altitude control and passive upright stability,” *IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (Algarve, Portugal, October 2012).
8. **S. B. Fuller** and R. M. Murray, “An insect-inspired autocorrelation model for visual flight control in a corridor,” *IEEE Int. Conf. Robotics and Biomimetics (ROBIO)* (Phuket, Thailand, December 2011).
9. A. Censi, S. Han, **S. B. Fuller** and R. Murray, “A bio-plausible method for attitude stabilization,” *IEEE Int. Conf. Decision and Control (CDC)* (Shanghai, China, January 2010).
10. M. Epstein, S. Waydo, **S. B. Fuller**, A. D. Straw, W. Dickson, M. H. Dickinson, and R. M. Murray, “Biologically inspired feedback design for *Drosophila* flight,” *American Control Conf. (ACC)* (New York, NY, June 2007).
11. S. Schell, A. Tretten, J. Burdick, **S. B. Fuller**, and P. Fiorini, “Hopper on wheels: evolving the hopping robot concept,” *IEEE Int. Conf. Field and Service Robotics (FSR)* (Helsinki, Finland, June 2001).
12. **S. B. Fuller** and J. M. Jacobson, “Ink Jet Fabricated Nanoparticle MEMS,” *IEEE Int. Conf. Microelectromechanical Systems* (Miyazaki, Japan, January 2000).

Workshops and Posters

1. **S. B. Fuller**, “Visual motion control in flies and fly-sized robots,” *Northeast Robotics Colloquium* (Cambridge, MA, 2013).
2. Z. E. Teoh, **S. B. Fuller**, A. Baisch, and R. J. Wood, “Pop-up book MEMS assembly of complex microrobots,” *Workshop on Meso-scale manufacturing, IEEE Int. Conf. Robotics and Automation (ICRA)* (Karlsruhe, Germany, 2013).

3. **S. B. Fuller**, A. D. Straw, R. M. Murray, and M. H. Dickinson, “Do flies use correlators to measure forward velocity?” poster in *Conf.: Visual Processing in Insects: from Anatomy to Behavior II*. (Howard Hughes Medical Institute Janelia Farm Research Campus, Ashburn, VA, May 2009).
4. **S. B. Fuller** and R. M. Murray, “A geometric analysis of Hassenstein-Reichardt correlators,” *Workshop on Visual guidance systems for small autonomous aerial vehicles, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)* (Nice, France, 2008).
5. **S. B. Fuller**, A. D. Straw, M. Epstein, S. Waydo, W. B. Dickson, M. H. Dickinson, and R. M. Murray, “Geometric analysis of Hassenstein-Reichardt elementary motion detectors and application to control in a fruit fly simulator and a robot,” *Int. Symp. Flying Insects and Robotics (FIR)* (Ascona, Switzerland, 2007).

Selected Invited Talks

1. **S. B. Fuller**, “Outperforming the fly: bio-inspired solutions to small-scale flight,” *Int. Conf. Micro Air Vehicles (IMAV)* (Delft Technical University, the Netherlands, August 2014). ([video link](#))
Opening Plenary Speaker
2. **S. B. Fuller**, “Outperforming the fly: bio-inspired solutions to small-scale flight,” MIT Enterprise Forum (Cambridge, MA, May 2014).
3. **S. B. Fuller**, “Outperforming the fly: bio-inspired solutions to small-scale flight,” University of California, San Diego (San Diego, CA, March 2014).
4. **S. B. Fuller**, “Outperforming the fly: bio-inspired solutions to small-scale flight,” Max Planck Institute (Munich, Germany, January 2014).
5. **S. B. Fuller**, “Flies and Robobees: at the intersection of robotics and biology” (MIT Aerospace Robotics and Embedded Systems Group (ARES), Cambridge, MA, November 2013).
6. **S. B. Fuller**, “Eclipsing the fly: bio-inspired solutions to small-scale flight” (D. E. Shaw, New York, NY, August 2013).
7. **S. B. Fuller**, “Eclipsing the fly: bio-inspired solutions to small-scale flight” (University of Rochester student robotics club, Rochester, NY, August 2013).
8. **S. B. Fuller**, “Eclipsing the fly: bio-inspired solutions to small-scale flight” (University of Edinburgh, Scotland, April 2013).
9. **S. B. Fuller**, “Feedback control strategies inspired by the fly” (NASA Jet Propulsion Laboratory, Pasadena, CA, May 2011).
10. **S. B. Fuller**, “Feedback control strategies inspired by the fly” (U. S. Army Research Laboratory, Adelphi, MD, March 2011).
11. **S. B. Fuller**, “Printing microchips and neuron bio-scaffolds by ink-jet” (University of Verona, Verona, Italy, 2004).
12. **S. B. Fuller**, “Printing microchips and neuron bio-scaffolds by ink-jet” (Nagoya University, Nagoya, Japan, 2002).

13. **S. B. Fuller**, “PEMS: Printed Micro-Electro Mechanical Systems,” *Things That Think* consortium meeting (MIT Media Laboratory, Cambridge, MA, 1999).
Selected as one of five lab-wide “research highlights” talks that year
14. **S. B. Fuller**, “Ink-jetting functional materials,” *Paper PC* Media Laboratory special interest group (MIT Media Laboratory, Cambridge, MA, 1999).

Miscellaneous

1. A. Censi, E. Frazzoli, and **S. B. Fuller**, “On the optimal codesign of vehicle sensing and actuation,” *Technical Report* (2014).
2. **S. B. Fuller**, M. Epstein, S. Waydo, W. B. Dickson, A. D. Straw, M. H. Dickinson, R. M. Murray, “Flight control in a flapping-wing fruit fly simulator,” *The Neuromorphic Engineer* (2007).

Patents

1. J. M. Jacobson, B. N. Hubert, B. Ridley, B. Nivi, and **S. B. Fuller**, “Nanoparticle-based electrical, chemical, and mechanical structures and methods of making same,” U.S. Patent 6,294,401 (Sept. 25, 2001).

Selected Press

The Scientist (Daily News), “[Insect-Inspired Sensors Improve Tiny Robot’s Flight](#)” (2014)

Science News, “[Robo-fly Steadies Flight with Onboard Sensor](#)” (2014)

The Daily Mail, “Flight of the Tiny Robo-fly: World’s Smallest Drone Weighs Less than a Gram and Navigates Using Light-Sensitive ‘Eyes’ ” (2014)

Boston Business Journal, “Harvard’s Robotic Bees Aim to Pollinate Crops, Search for Survivors in Rubble” (2014)

Phys.org, “[Antennae Help Flies ‘Cruise’ in Gusty Winds](#)” (2014)

RedOrbit.com, “[Fruit Flies Use Not Just Eyes, but Antennae to Control Air Speed](#)” (2014)

Wired.com, “[Watch Harvard’s Teeny-Tiny Robotic Insect Take Flight](#)” (2013)

The New York Times, “[A Remote-Controlled Robot the Size of a Fly](#)” (2013)

The Economist, “[Robodiptera: Miniature Flying Robots](#)” (2013)

German National Radio Deutschlandfunk, “Mechanische Mücke (Mechanical Mosquito),” radio interview (2013)

MIT News, “Biology: the ultimate robotics” (2003)

NASA Tech Briefs, “Hopping Robot With Wheels: Hopping and Wheeled Motions Complement Each Other” (2002)

Science News, “Hop...Hop...Hopbots! Designers of Small, Mobile Robots Take Cues from Grasshoppers and Frogs” (2001)

MIT Technology Review, “[Print Your Next PC: Research at MIT’s Media Lab Could Make it Possible to Print Out Hardware Right on the Desktop](#)” (2000)

Cover article

Selected Service

Public demonstrations, Boston-area science fairs (2014-2015)

Public lecture, Cambridge Entomological Society (2014)

Public demonstration, Boston Museum of Science Robot Block Party (2012)

Reviewer, *IEEE Conferences* (2008-present)

Reviewer, *Proceedings of the IEEE* (2014)

Reviewer, *J. Royal Society Interface* (2013-present)