REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY): 13-07-2015

2. REPORT TYPE: Final Report

3. DATES COVERED (From - To): 1-Oct-2009 - 31-Mar-2015

4. TITLE AND SUBTITLE: Final Report: Development of Fully-Integrated Micromagnetic Actuator Technologies

5a. CONTRACT NUMBER: W911NF-09-1-0511

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER: 611103

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
David P. Arnold

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Florida Office of Engineering
339 Weil Hall

Gainesville, FL 32611 -6550

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S): ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S): 54690-EG-PCS.33

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Objectives
The primary objective of this research was to transition high-performance micromagnets into fully-integrated, batch-fabricated micromagnetic actuators for Army-specified applications, such as microscale flow-control actuators. Magnetically-based electromechanical actuation schemes are ubiquitous in macroscale systems such as audio speakers, relays, solenoids, and electrical motors. However, implementation of these transduction schemes at

15. SUBJECT TERMS
MEMS, magnetic materials, microactuators, microfabrication, synthetic jet actuators, flow control, plasma actuators, energy conversion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		David Arnold
					19b. TELEPHONE NUMBER: 352-392-4931

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Development of Fully-Integrated Micromagnetic Actuator Technologies

ABSTRACT

Objectives

The primary objective of this research was to transition high-performance micromagnets into fully-integrated, batch-fabricated micromagnetic actuators for Army-specified applications, such as microscale flow-control actuators. Magnetically-based electromechanical actuation schemes are ubiquitous in macroscale systems such as audio speakers, relays, solenoids, and electrical motors. However, implementation of these transduction schemes at the microscale is nearly nonexistent because of certain design and fabrication challenges—primarily the inability to integrate high-performance, permanent-magnet (magnetically-hard) films within more complex micromachined structures. As a consequence, most microfabricated transducers rely on other transduction mechanisms (e.g. electrostatic, piezoelectric, thermoelastic). However, these mechanisms limit the actuation force, stroke (displacement), power density, and efficiency necessary for certain applications. To enable the development of high-performance magnetic actuator technologies, the original research plan was organized into three specific technical objectives:

Objective 1: Evaluate and systematically characterize the integrability of newly developed permanent-magnet materials in more complex microfabrication process flows

Objective 2: Design, model, and optimize a novel multi-magnet electrodynamic actuation scheme that is suitable for planar batch microfabrication

Objective 3: Fabricate and characterize a fully-integrated out-of-plane actuator using silicon-based and/or printed-circuit-board based fabrication strategies

---

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/10/2015	28.00	Shashank G. Sawant, Ilan Eskinazi, Mark Sheplak, Louis N. Cattafesta, David P. Arnold. Comparative Study of Two Methods for Driving Electrodynamic Zero-Net Mass-Flux Actuators, AIAA Journal, (09 2013): 0. doi: 10.2514/1.J052378
07/10/2015	29.00	Alexandra Garraud, Ololade D. Oniku, David P. Arnold. Influence of temperature on the magnetic properties of electroplated L10 CoPt thick films, Journal of Applied Physics, (05 2015): 0. doi: 10.1063/1.4913890
08/06/2012	8.00	Shashank G. Sawant, Matias Oyarzun, Mark Sheplak, Louis N. Cattafesta III, David P. Arnold. Modeling of Electrodynamic Zero-Net Mass-Flux Actuators, AIAA Journal, (06 2012): 1347. doi:
08/16/2013	19.00	Vinod R Challa, Jose Oscar Mur-Miranda, David P Arnold. Wireless power transmission to an electromechanical receiver using low-frequency magnetic fields, Smart Materials and Structures, (11 2012): 0. doi: 10.1088/0964-1726/21/11/115017
08/16/2013	21.00	Ololade D Oniku, Benjamin J Bowers, Sheetal B Shetye, Naigang Wang, David P Arnold. Permanent magnet microstructures using dry-pressed magnetic powders, Journal of Micromechanics and Microengineering, (07 2013): 0. doi: 10.1088/0960-1317/23/7/075027
08/16/2013	20.00	Shuo Cheng, David P Arnold, Vinod R Challa. The role of coupling strength in the performance of electrodynamic vibrational energy harvesters, Smart Materials and Structures, (02 2013): 0. doi: 10.1088/0964-1726/22/2/025005
08/18/2014	22.00	Naigang Wang, Mina S. Hanna, Curtis R. Taylor, David P. Arnold, Shashank G. Sawant. Fabrication, characterization, and modeling of fully-batch-fabricated piston-type electrodynamic microactuators, Journal of Microelectromechanical Systems, (02 2014): 220. doi:
08/18/2014	23.00	David P. Arnold, Shuo Cheng. Defining the coupling coefficient for electrodynamic transducers, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, (11 2013): 3561. doi:
08/18/2014	24.00	Shuo Cheng, David P. Arnold. Microfabricated electrodynamic transformers for electromechanical power conversion, Journal of Micromechanics and Microengineering, (11 2013): 114002. doi:
08/19/2010	3.00	David P. Arnold, Naigang Wang. Permanent magnets for MEMS, Journal of Microelectromechanical Systems, (12 2009): . doi:
08/19/2010	2.00	Naigang Wang, David P. Arnold. Fully Batch-Fabricated MEMS Magnetic Vibrational Energy Harvesters, , (12 2009): . doi:
08/19/2010	4.00	Naigang Wang, David P. Arnold. Batch-fabricated electrodynamic microactuators with integrated micromagnets, IEEE Transactions on Magnetics, (06 2010): . doi:
08/23/2011	5.00	Tzu-Shun Yang, Naigang Wang, David P. Arnold. Morphology and magnetic properties of electroplated Co-rich Co-Zn thin films, Microsystem Technologies, (01 2011): 85. doi: 10.1007/s00542-010-1144-3

08/23/2011	6.00	Tzu-Shun Yang, Naigang Wang, David P. Arnold. Fabrication and characterization of parylene-bonded Nd–Fe–B powder micromagnets, Journal of Applied Physics, (04 2011): 0. doi: 10.1063/1.3566001

TOTAL: **14**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

07/13/2015 30.00 Bin Qi, David P. Arnold. Fabrication of size-tunable monodisperse Nd2Fe14B-CoFe2 nanocomplexes, 23rd Intl. Workshop on Rare Earth and Future Permanent Magnets and Their Applications (REPM 2014). 01-AUG-14, . : ,

07/13/2015 32.00 Ololade D. Oniku, Bin Qi, David P. Arnold. Effect of current density on electroplated CoPt thick films, 18th Int. Conf. Solid-State Sensors, Actuators, and Microsystems (Transducers 2015). 20-JUN-15, . : ,

07/13/2015 31.00 Shashank G. Sawant, Eric A. Deem, Dominic J. Agentis, Louis N. Cattafesta, David P. Arnold. Chip-scale electrodynamic synthetic jet actuators, 28th IEEE Conf. Micro Electro Mechanical Systems (MEMS 2015). 19-JAN-15, . : ,

08/06/2012 9.00 Justin C. Zito, David P. Arnold, Tomas Houba, Jignesh Soni, Ryan J. Durscher, Subrata Roy. Microscale dielectric barrier discharge plasma actuators: performance characterization and numerical comparison, 43rd AIAA Plasmadynamics and Lasers Conference. 25-JUN-12, . : ,

08/06/2012 13.00 Benjamin J. Bowers, Ololade D. Oniku, David P. Arnold. Microfabrication and process integration of powder-based permanent magnets, Technologies for Future Micro-Nano Manufacturing. 08-AUG-12, . : ,

08/06/2012 12.00 Ololade D. Oniku, David P. Arnold. High-energy-density permanent micromagnets formed from heterogeneous magnetic powder mixtures, Proc. 25th IEEE Conf. Micro Electro Mechanical Systems (MEMS 2012). 29-JAN-12, . : ,

08/06/2012 11.00 Justin C. Zito, Ryan J. Durscher, Jignesh Soni, Subrata Roy, David P. Arnold. Mechano-fluidic characterization of microscale dielectric barrier discharge plasma actuators, Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2012). 03-JUN-12, . : ,

08/06/2012 10.00 Shashank G. Sawant└, Ilan Eskinazi, Mark Sheplak, Louis N. Cattafesta. III, David P. Arnold. A Comparative Study of Two Methods for DrivingElectrodynamic Zero-Net-Mass-Flux Actuators, 6th AIAA Flow Control Conference. 25-JUN-12, . : ,

08/16/2013 16.00 Justin C. Zito, David P. Arnold, Ryan J. Durscher, Subrata Roy. Exploration of ceramic dielectrics for microscale dielectric barrier discharge plasma actuators, 44th AIAA Plasmadynamics and Lasers Conf., San Diego, CA, AIAA Paper 2013-2495, 23 pages. 01-JUN-13, . : ,

08/16/2013 18.00 Shuo Cheng, David P. Arnold. Demonstration of a micromachined electrodynamic transformer and application in a resonant dc/ac power inverter, 12th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2012), Atlanta, GA. 01-DEC-12, . : ,

08/16/2013 17.00 Vinod R. Challa, David P. Arnold. MEMS electrodynamic vibrational energy harvesters using multi-pole magnetic architectures, 12th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2012), Atlanta, GA. 01-DEC-12, . : ,

08/18/2014 25.00 William C. Patterson, Evan E. Shorman, Nicolas Garraud, David P. Arnold. A magneto-optical microscope for quantitative mapping of the stray fields from magnetic microstructures, Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2014). 09-JUN-14, . : ,

08/18/2014 26.00 Ololade D. Oniku, Alexandra Garraud, Evan E. Shorman, William C. Patterson, David P. Arnold. Modeling of a micromagnetic imprinting process,
Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2014). 09-JUN-14, . : ,

TOTAL: 13

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Shashank Sawant	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Bin Qi	0.12
FTE Equivalent:	**0.12**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
David Arnold	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Shashank Sawant

Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The key contributions of this research effort to each of the aforementioned applications are noted below:

Application 1: Synthetic jet actuators for flow control

- A completely micro-fabricated electrodynamic synthetic jet actuator design was realized with the dimension 7.5 mm x 7.5 mm x 1.1 mm, making it the smallest known electrodynamic synthetic jet actuator.
- The component of the μeZNMF actuator (Figure 1), including the diaphragm with NdFeB bonded powder magnets, were batch fabricated using silicon micromachining processes, making it the only known fully micro-fabricated electrodynamic synthetic jet actuator.
- Particle Image Velocimetry (PIV) experiments (Figure 1) were performed and a maximum output velocity of 4.29 m/s was measured for an input current of 200 mApp for an input power of just 20 mW.

Application 2: Dielectric barrier discharge plasma actuators for flow control

- Reduced-size or microscale DBD actuators were manufactured using semiconductor fabrication techniques with electrode dimensions as narrow as 10 μm, and utilizing silicon dioxide (SiO2) for the dielectric barrier having thicknesses of 5 and 10 μm (Figure 2).
- The micro DBD plasma actuators (Figure 2) were characterized for electrical (power consumption), fluidic (induced velocity) and mechanical (thrust and plasma body force) performance. Velocities reaching up to 1.5 m/s while consuming 41 W/m of electrical power (normalized by electrode length) were measured. The plasma body force (acting on the fluid) and thrust (reaction force felt by the actuator) were measured to be 2.5 and 1.4 mN/m, respectively.
- Device failure mechanisms were analyzed and attributed primarily to erosion and breakdown of the dielectric barrier, leading to excessive current densities and catastrophic “burn-out” of the barrier material

Application 3: Electrodynamic transducers for energy conversion

- A crucial design parameter, denoted “coupling strength”, was theoretically identified and experimentally measured for maximizing the electromechanical effectiveness of electrodynamic architectures.
- Developed and demonstrated first-generation, fully microfabricated ~9 mm3 vibrational energy harvesting device (Figure 3) that utilized a multi-pole magnetic architecture and yielded a power output of 171 pW at 4 g acceleration, corresponding to a volumetric power density of ~20 nW/cm3.
- Investigated electrodynamic transducers for enabling a unique, wireless power transmission scheme, and demonstrated delivery of 150 μW of power at 12% efficiency to a compact receiver at a distance of 2.2 cm at a transmission frequency of only 38 Hz.
- Developed and demonstrated a two-port 10 mm3 electrodynamic transducer, coined as an “electrodynamic transformer” to enable energy-dense electrical power conversion using vibrating mechanical structures rather than traditional magnetic-core transformers. Achieved a power transfer efficiency of 40% with first-run prototypes, and demonstrated an ultra-low-voltage dc/ac inverter based on the ET using only two external components—a MOSFET and a capacitor.

Collaborations and Technology Transfer
- None

Resulting Journal Publications during Reporting Period

D. P. Arnold and N. Wang, “Permanent magnets for MEMS,” J. Microelectromech. Syst., vol. 18, no. 6, pp. 1255-1266, Dec. 2009.
N. Wang and D. P. Arnold, “Batch-fabricated electrodynamic microactuators with integrated micromagnets,” IEEE Trans. Magn., vol. 46, no. 6, pp. 1798-1801, June 2010.
T.-S. Yang, N. Wang, and D. P. Arnold, “Morphology and magnetic properties of electroplated Co-rich Co-Zn thin films,” Microsyst. Tech., vol. 17, no. 1, pp. 85-91, Jan. 2011.
T.-S. Yang, N. Wang, and D. P. Arnold, “Fabrication and characterization of parylene-bonded Nd–Fe–B powder micromagnets,” J. Appl. Phys., vol. 109, no. 7, 07A753, 3 pages, April 2011.
J. Zito, R. J. Durscher, J. Soni, S. Roy, and D. P. Arnold, “Flow and force inducement using micron size dielectric barrier discharge actuators,” Appl. Phys. Lett., vol. 100, no. 19, 193502, 4 pages, May 2012.
S. G. Sawant, M. Oyarzun, M. Sheplak, L. N. Cattafesta III, and D. P. Arnold, “Modeling of electrodynamic zero-net mass-flux actuators,” AIAA Journal, vol. 50, no. 6, June 2012.
V. R. Challa, J. O. Mur-Miranda, and D. P. Arnold, “Wireless power transmission to an electromechanical receiver using low-frequency magnetic fields,” Smart Mater. Struct., vol. 21, no. 11, 115017, 11 pages, Nov. 2012.

V. R. Challa, S. Cheng, and D. P. Arnold, “The role of coupling strength in the performance of electrodynamic vibrational energy harvesters,” Smart Mater. Struct., vol. 22, no. 2, 025005, 11 pages, Feb. 2013.

O. D. Oniku, B. J. Bowers, S. B. Shetye, N. Wang, and D. P. Arnold, “Permanent magnet microstructures using dry-pressed magnetic powders,” J. Micromech. Microeng., vol. 23, no. 7, 075027, 11 pages, July 2013.

S. G. Sawant, I. Eskinazi, M. Sheplak, L. N. Cattafesta, III, and D. P. Arnold, “Comparative study of two methods for driving electrodynamic zero-net mass-flux actuators,” AIAA Journal, vol. 51, no. 9, pp. 2286–2290, Jul. 2013.

S. Cheng and D. P. Arnold “Defining the coupling coefficient for electrodynamic transducers,” J. Acous. Soc. Amer., vol. 134, no. 5, pp. 3561-3572, Nov. 2013.

S. Cheng and D. P. Arnold, “Microfabricated electrodynamic transformers for electromechanical power conversion,” J. Micromech. Microeng., vol. 23, no. 11, 114002, 10 pages, Nov. 2013.

S. G. Sawant, N. Wang, M. Hanna, C. R. Taylor, and D. P. Arnold, “Fabrication, characterization, and modeling of fully-batch-fabricated piston-type electrodynamic microactuators,” J. Microelectromech. Syst., vol. 23, no. 1, pp. 220-229, Feb. 2014.

A. Garraud, O. D. Oniku, and D. P. Arnold, “Influence of temperature on the magnetic properties of electroplated L10 CoPt thick films,” J. Appl. Phys., vol. 117, no. 17, 17C718, 4 pages, May 2015.

Resulting Conference Publications during Reporting Period

N. Wang and D. P. Arnold, “Fully batch-fabricated MEMS magnetic vibrational energy harvesters,” Tech. Dig. 9th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2009), Washington, DC, Dec. 2009, pp. 348-351.

B. J. Bowers, O. D. Oniku, and D. P. Arnold, “Microfabrication and process integration of powder-based permanent magnets,” Technologies for Future Micro-Nano Manufacturing, Napa, CA, Aug. 2011, pp. 162-165.

O. D. Oniku and D. P. Arnold, “High-energy-density permanent micromagnets formed from heterogeneous magnetic powder mixtures,” Proc. 25th IEEE Conf. Micro Electro Mechanical Systems (MEMS 2012), Paris, France, Jan. 2012, pp. 436-439.

S. G. Sawant, I. Eskinazi, M. Sheplak, L. N. Cattafesta, III, and D. P. Arnold, “A comparative study of two methods for driving electrodynamic zero-net-mass-flux actuators,” 6th AIAA Flow Control Conf., New Orleans, LA, Jun. 2012, AIAA Paper 2012-3241, 9 pages.

J. C. Zito, D. P. Arnold, T. Houba, J. Soni, R. J. Durscher, and S. Roy, “Microscale dielectric barrier discharge plasma actuators: performance characterization and numerical comparison,” 43rd AIAA Plasmadynamics and Lasers Conf., New Orleans, LA, Jun. 2012, AIAA Paper 2012-3091, 14 pages.

J. C. Zito, R. J. Durscher, J. Soni, S. Roy, and D. P. Arnold, “Mechano-fluidic characterization of microscale dielectric barrier discharge plasma actuators,” Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2012), Hilton Head, SC, June 2012, pp. 22-25.

S. Cheng and D. P. Arnold, “Demonstration of a micromachined electrodynamic transformer and application in a resonant dc/ac power inverter,” Tech. Dig. 12th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2012), Atlanta, GA, Dec. 2012, pp. 76-79.

V. R. Challa and D. P. Arnold, “MEMS electrodynamic vibrational energy harvesters using multi-pole magnetic architectures,” Tech. Dig. 12th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2012), Atlanta, GA, Dec. 2012, pp. 6-9.

J. C. Zito, D. P. Arnold, R. J. Durscher, and S. Roy, “Exploration of ceramic dielectrics for microscale dielectric barrier discharge plasma actuators,” 44th AIAA Plasmadynamics and Lasers Conf., San Diego, CA, Jun. 2013, AIAA Paper 2013-2495, 23 pages.

W. C. Patterson, E. E. Shorman, N. Garraud, and D. P. Arnold, “A magneto-optical microscope for quantitative mapping of the stray fields from magnetic microstructures,” Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2014), Hilton Head, SC, June 2014, pp. 359-362.

O. D. Oniku, A. Garraud, E. E. Shorman, W. C. Patterson, and D. P. Arnold, “Modeling of a micromagnetic imprinting process,” Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2014), Hilton Head, SC, June 2014, pp. 187-190.

B. Qi and D. P. Arnold, “Fabrication of size-tunable monodisperse Nd2Fe14B@CoFe2 nanocomplexes,” 23rd Intl. Workshop on Rare Earth and Future Permanent Magnets and Their Applications (REPM 2014), Annapolis, MD, Aug. 2014, pp. 323-325.

S. G. Sawant, E. A. Deem, D. J. Agentis, L. N. Cattafesta, and D. P. Arnold. “Chip-scale electrodynamic synthetic jet actuators,” Proc. 28th IEEE Conf. Micro Electro Mechanical Systems (MEMS 2015), Estoril, Portugal, Jan. 2015, pp. 936-939.

O. D. Oniku, B. Qi, and D. P. Arnold, “Effect of current density on electroplated CoPt thick films,” Tech. Dig. 18th Int. Conf. Solid-State Sensors, Actuators, and Microsystems (Transducers 2015), Anchorage, AK, June 2015, pp. 596-601.

Dissertations

N. Wang, “Fabrication and Integration of Permanent Magnet Materials into MEMS Transducers,” University of Florida, May 2010.

J. Zito, “Investigation of Microscale Dielectric Barrier Discharge Plasma Devices,” University of Florida, August 2013.

S. Sawant, “Design, Fabrication and Characterization of Micro-Electrodynamic-Zero-Net-Mass-Flux Actuators,” University of Florida, August 2015.

Technology Transfer

Final Project Summary - Grant # W911NF-09-1-0511

(Reporting Period: October 1, 2009–March 31, 2015)

Development of Fully-Integrated Micromagnetic Actuator Technologies

Prof. David P. Arnold
University of Florida
Department of Electrical and Computer Engineering
Interdisciplinary Microsystems Group (IMG)
213 Larsen Hall
Gainesville, FL 32611

Objectives

The primary objective of this research was to transition high-performance micromagnets into fully-integrated, batch-fabricated micromagnetic actuators for Army-specified applications, such as microscale flow-control actuators. Magnetically-based electromechanical actuation schemes are ubiquitous in macroscale systems such as audio speakers, relays, solenoids, and electrical motors. However, implementation of these transduction schemes at the microscale is nearly nonexistent because of certain design and fabrication challenges—primarily the inability to integrate high-performance, permanent-magnet (magnetically-hard) films within more complex micromachined structures. As a consequence, most microfabricated transducers rely on other transduction mechanisms (e.g. electrostatic, piezoelectric, thermoelastic). However, these mechanisms limit the actuation force, stroke (displacement), power density, and efficiency necessary for certain applications. To enable the development of high-performance magnetic actuator technologies, the original research plan was organized into three specific technical objectives:

<u>Objective 1:</u> Evaluate and systematically characterize the integrability of newly developed permanent-magnet materials in more complex microfabrication process flows

<u>Objective 2:</u> Design, model, and optimize a novel multi-magnet electrodynamic actuation scheme that is suitable for planar batch microfabrication

<u>Objective 3:</u> Fabricate and characterize a fully-integrated out-of-plane actuator using silicon-based and/or printed-circuit-board based fabrication strategies

Approach

Over the 5+ year period of performance, efforts in pursuit of the above research objectives have evolved and broadened. New magnetic materials and relevant fabrication methods were developed, and their compatibility with silicon microfabrication techniques was investigated. These materials and methods were used to demonstrate 3 different microsystem devices/applications:

Application 1: Synthetic jet actuators for flow control – development of micro electrodynamic Zero Net Mass Flux (μeZNMF) actuators for flow control applications

Application 2: Dielectric barrier discharge (DBD) plasma actuators for flow control[1] – development of microfabricated DBD plasma actuators for flow control applications

Application 3: Electrodynamic transducers for energy conversion - exploiting electrodynamic interactions between permanent magnets and coils to enact different electromechanical energy conversion functionalities (actuators, energy harvesters, motors/generators, electrical power conversion).

Relevance to the Army

Microscale flow-control actuators can be used as flight-control effectors for low-Reynolds-number air vehicles. The actuators can lend themselves to flapless, tail-less and low cross-section design. Such designs could lead to efficient and stealthier successors of the currently operational UAVS like the RQ-11, Switchblade or Wasp III. Additionally, high-power-density energy converters are very important in electronic power systems, especially for soldier-borne electronics. More broadly, integrated micromagnet technologies have numerous other military and consumer applications in electronics, microrobotics, biomedical devices, RF components, power systems, etc.

Accomplishments

The key contributions of this research effort to each of the aforementioned applications are noted below:

Application 1: Synthetic jet actuators for flow control

- A completely micro-fabricated electrodynamic synthetic jet actuator design was realized with the dimension 7.5 mm x 7.5 mm x 1.1 mm, making it the smallest known electrodynamic synthetic jet actuator.
- The component of the μeZNMF actuator (Figure 1), including the diaphragm with NdFeB bonded powder magnets, were batch fabricated using silicon micromachining processes, making it the only known fully micro-fabricated electrodynamic synthetic jet actuator.
- Particle Image Velocimetry (PIV) experiments (Figure 1) were performed and a maximum output velocity of 4.29 m/s was measured for an input current of 200 mA_{pp} for an input power of just 20 mW.

[1] While this technology does not necessitate the use of integrated magnets, the ability to microfabricate plasma actuators developed as an unexpected area for investigation. Magnetic materials may be integrated into future device designs to enhance the plasma density and effectiveness of the actuators.

Application 2: Dielectric barrier discharge plasma actuators for flow control

- Reduced-size or microscale DBD actuators were manufactured using semiconductor fabrication techniques with electrode dimensions as narrow as 10 μm, and utilizing silicon dioxide (SiO_2) for the dielectric barrier having thicknesses of 5 and 10 μm (Figure 2).
- The micro DBD plasma actuators (Figure 1) were characterized for electrical (power consumption), fluidic (induced velocity) and mechanical (thrust and plasma body force) performance. Velocities reaching up to 1.5 m/s while consuming 41 W/m of electrical power (normalized by electrode length) were measured. The plasma body force (acting on the fluid) and thrust (reaction force felt by the actuator) were measured to be 2.5 and 1.4 mN/m, respectively.
- Device failure mechanisms were analyzed and attributed primarily to erosion and breakdown of the dielectric barrier, leading to excessive current densities and catastrophic "burn-out" of the barrier material

Application 3: Electrodynamic transducers for energy conversion

- A crucial design parameter, denoted "coupling strength", was theoretically identified and experimentally measured for maximizing the electromechanical effectiveness of electrodynamic architectures.
- Developed and demonstrated first-generation, fully microfabricated ~9 mm^3 vibrational energy harvesting device (Figure 3) that utilized a multi-pole magnetic architecture and yielded a power output of 171 pW at 4 g acceleration, corresponding to a volumetric power density of ~20 nW/cm^3.
- Investigated electrodynamic transducers for enabling a unique, wireless power transmission scheme, and demonstrated delivery of 150 μW of power at 12% efficiency to a compact receiver at a distance of 2.2 cm at a transmission frequency of only 38 Hz.
- Developed and demonstrated a two-port 10 mm^3 electrodynamic transducer, coined as an "electrodynamic transformer" to enable energy-dense electrical power conversion using vibrating mechanical structures rather than traditional magnetic-core transformers. Achieved a power transfer efficiency of 40% with first-run prototypes, and demonstrated an ultra-low-voltage dc/ac inverter based on the ET using only two external components—a MOSFET and a capacitor.

Collaborations and Technology Transfer

- None

Resulting Journal Publications during Reporting Period

D. P. Arnold and N. Wang, “Permanent magnets for MEMS,” J. Microelectromech. Syst., vol. 18, no. 6, pp. 1255-1266, Dec. 2009.

N. Wang and D. P. Arnold, “Batch-fabricated electrodynamic microactuators with integrated micromagnets,” IEEE Trans. Magn., vol. 46, no. 6, pp. 1798-1801, June 2010.

T.-S. Yang, N. Wang, and D. P. Arnold, “Morphology and magnetic properties of electroplated Co-rich Co-Zn thin films,” *Microsyst. Tech.*, vol. 17, no. 1, pp. 85-91, Jan. 2011.

T.-S. Yang, N. Wang, and D. P. Arnold, “Fabrication and characterization of parylene-bonded Nd–Fe–B powder micromagnets,” *J. Appl. Phys.*, vol. 109, no. 7, 07A753, 3 pages, April 2011.

J. Zito, R. J. Durscher, J. Soni, S. Roy, and D. P. Arnold, “Flow and force inducement using micron size dielectric barrier discharge actuators,” *Appl. Phys. Lett.*, vol. 100, no. 19, 193502, 4 pages, May 2012.

S. G. Sawant, M. Oyarzun, M. Sheplak, L. N. Cattafesta III, and D. P. Arnold, “Modeling of electrodynamic zero-net mass-flux actuators,” *AIAA Journal*, vol. 50, no. 6, June 2012.

V. R. Challa, J. O. Mur-Miranda, and D. P. Arnold, “Wireless power transmission to an electromechanical receiver using low-frequency magnetic fields,” Smart Mater. Struct., vol. 21, no. 11, 115017, 11 pages, Nov. 2012.

V. R. Challa, S. Cheng, and D. P. Arnold, “The role of coupling strength in the performance of electrodynamic vibrational energy harvesters,” Smart Mater. Struct., vol. 22, no. 2, 025005, 11 pages, Feb. 2013.

O. D. Oniku, B. J. Bowers, S. B. Shetye, N. Wang, and D. P. Arnold, “Permanent magnet microstructures using dry-pressed magnetic powders,” J. Micromech. Microeng., vol. 23, no. 7, 075027, 11 pages, July 2013.

S. G. Sawant, I. Eskinazi, M. Sheplak, L. N. Cattafesta, III, and D. P. Arnold, “Comparative study of two methods for driving electrodynamic zero-net mass-flux actuators,” *AIAA Journal*, vol. 51, no. 9, pp. 2286–2290, Jul. 2013.

S. Cheng and D. P. Arnold “Defining the coupling coefficient for electrodynamic transducers,” J. Acous. Soc. Amer., vol. 134, no. 5, pp. 3561-3572, Nov. 2013.

S. Cheng and D. P. Arnold, “Microfabricated electrodynamic transformers for electromechanical power conversion,” J. Micromech. Microeng., vol. 23, no. 11, 114002, 10 pages, Nov. 2013.

S. G. Sawant, N. Wang, M. Hanna, C. R. Taylor, and D. P. Arnold, “Fabrication, characterization, and modeling of fully-batch-fabricated piston-type electrodynamic microactuators,” J. Microelectromech. Syst., vol. 23, no. 1, pp. 220-229, Feb. 2014.

A. Garraud, O. D. Oniku, and D. P. Arnold, “Influence of temperature on the magnetic properties of electroplated $L1_0$ CoPt thick films,” *J. Appl. Phys.*, vol. 117, no. 17, 17C718, 4 pages, May 2015.

Resulting Conference Publications during Reporting Period

N. Wang and D. P. Arnold, “Fully batch-fabricated MEMS magnetic vibrational energy harvesters,” Tech. Dig. 9th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2009), Washington, DC, Dec. 2009, pp. 348-351.

B. J. Bowers, O. D. Oniku, and D. P. Arnold, “Microfabrication and process integration of powder-based permanent magnets,” Technologies for Future Micro-Nano Manufacturing, Napa, CA, Aug. 2011, pp. 162-165.

O. D. Oniku and D. P. Arnold, “High-energy-density permanent micromagnets formed from heterogeneous magnetic powder mixtures,” Proc. 25th IEEE Conf. Micro Electro Mechanical Systems (MEMS 2012), Paris, France, Jan. 2012, pp. 436-439.

S. G. Sawant, I. Eskinazi, M. Sheplak, L. N. Cattafesta, III, and D. P. Arnold, “A comparative study of two methods for driving electrodynamic zero-net-mass-flux actuators,” 6th AIAA Flow Control Conf., New Orleans, LA, Jun. 2012, AIAA Paper 2012-3241, 9 pages.

J. C. Zito, D. P. Arnold, T. Houba, J. Soni, R. J. Durscher, and S. Roy, “Microscale dielectric barrier discharge plasma actuators: performance characterization and numerical comparison,” 43rd AIAA Plasmadynamics and Lasers Conf., New Orleans, LA, Jun. 2012, AIAA Paper 2012-3091, 14 pages.

J. C. Zito, R. J. Durscher, J. Soni, S. Roy, and D. P. Arnold, “Mechano-fluidic characterization of microscale dielectric barrier discharge plasma actuators,” Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2012), Hilton Head, SC, June 2012, pp. 22-25.

S. Cheng and D. P. Arnold, “Demonstration of a micromachined electrodynamic transformer and application in a resonant dc/ac power inverter,” Tech. Dig. 12th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2012), Atlanta, GA, Dec. 2012, pp. 76-79.

V. R. Challa and D. P. Arnold, “MEMS electrodynamic vibrational energy harvesters using multi-pole magnetic architectures,” Tech. Dig. 12th Int. Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Apps. (PowerMEMS 2012), Atlanta, GA, Dec. 2012, pp. 6-9.

J. C. Zito, D. P. Arnold, R. J. Durscher, and S. Roy, "Exploration of ceramic dielectrics for microscale dielectric barrier discharge plasma actuators," 44th AIAA Plasmadynamics and Lasers Conf., San Diego, CA, Jun. 2013, AIAA Paper 2013-2495, 23 pages.

W. C. Patterson, E. E. Shorman, N. Garraud, and D. P. Arnold, "A magneto-optical microscope for quantitative mapping of the stray fields from magnetic microstructures," Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2014), Hilton Head, SC, June 2014, pp. 359-362.

O. D. Oniku, A. Garraud, E. E. Shorman, W. C. Patterson, and D. P. Arnold, "Modeling of a micromagnetic imprinting process," Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head 2014), Hilton Head, SC, June 2014, pp. 187-190.

B. Qi and D. P. Arnold, "Fabrication of size-tunable monodisperse $Nd_2Fe_{14}B@CoFe_2$ nanocomplexes," 23rd Intl. Workshop on Rare Earth and Future Permanent Magnets and Their Applications (REPM 2014), Annapolis, MD, Aug. 2014, pp. 323-325.

S. G. Sawant, E. A. Deem, D. J. Agentis, L. N. Cattafesta, and D. P. Arnold. "Chip-scale electrodynamic synthetic jet actuators," Proc. 28th IEEE Conf. Micro Electro Mechanical Systems (MEMS 2015), Estoril, Portugal, Jan. 2015, pp. 936-939.

O. D. Oniku, B. Qi, and D. P. Arnold, "Effect of current density on electroplated CoPt thick films," Tech. Dig. 18th Int. Conf. Solid-State Sensors, Actuators, and Microsystems (Transducers 2015), Anchorage, AK, June 2015, pp. 596-601.

Dissertations

N. Wang, "Fabrication and Integration of Permanent Magnet Materials into MEMS Transducers," University of Florida, May 2010.

J. Zito, "Investigation of Microscale Dielectric Barrier Discharge Plasma Devices," University of Florida, August 2013.

S. Sawant, "Design, Fabrication and Characterization of Micro-Electrodynamic-Zero-Net-Mass-Flux Actuators," University of Florida, August 2015.

Figures

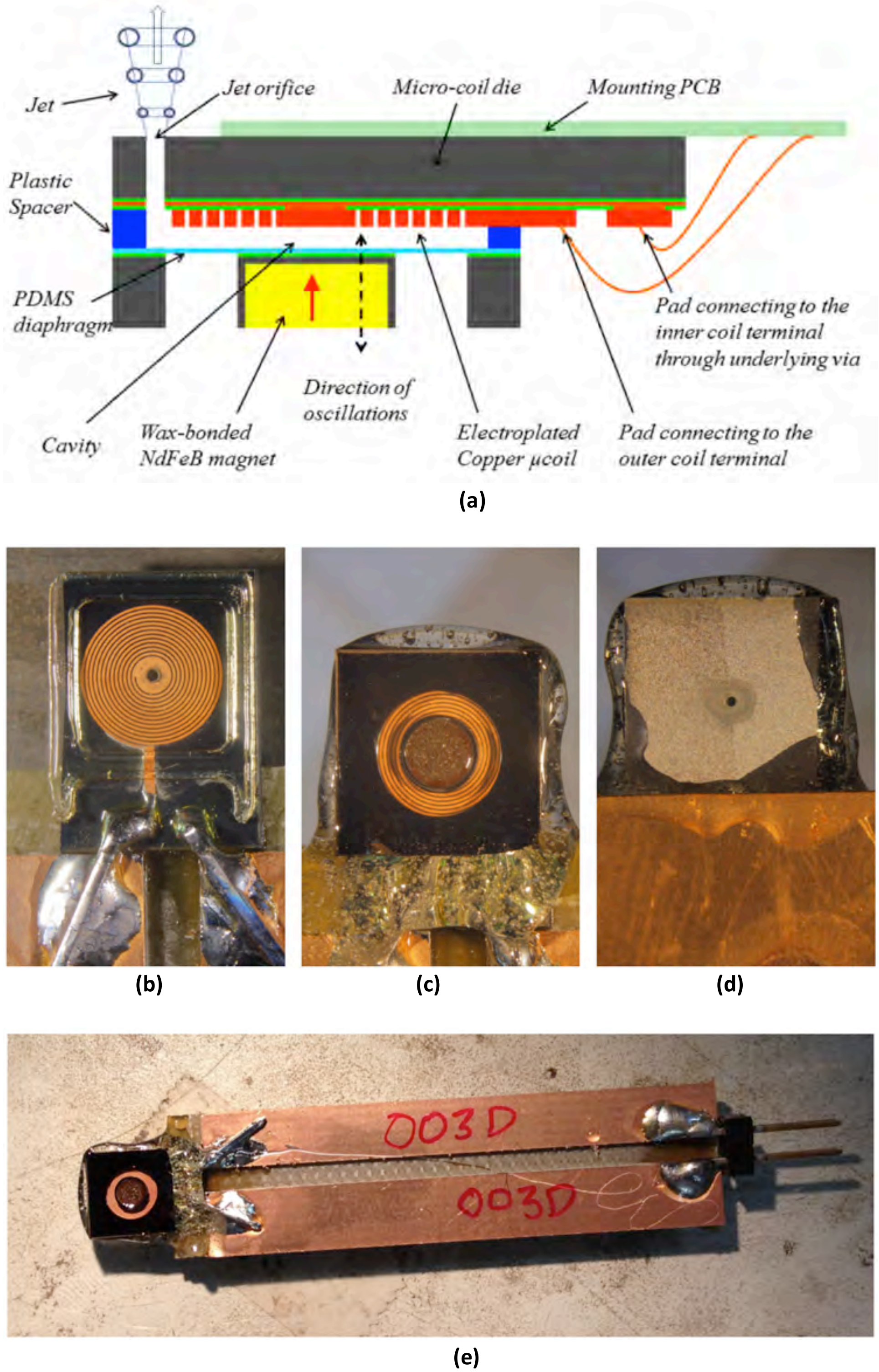

Figure 1:The µeZNMF actuator: (a) schematic of the actuator, (b) actuator coil die with a laser-cut orifice in the center and a *double sided tape* spacer at the periphery, (c) top view of the actuator assembled by placing the magnet die on the coil die, (d) actuator's bottom view from the side of the coil die, and (e) the position of the actuator on its test circuit board.

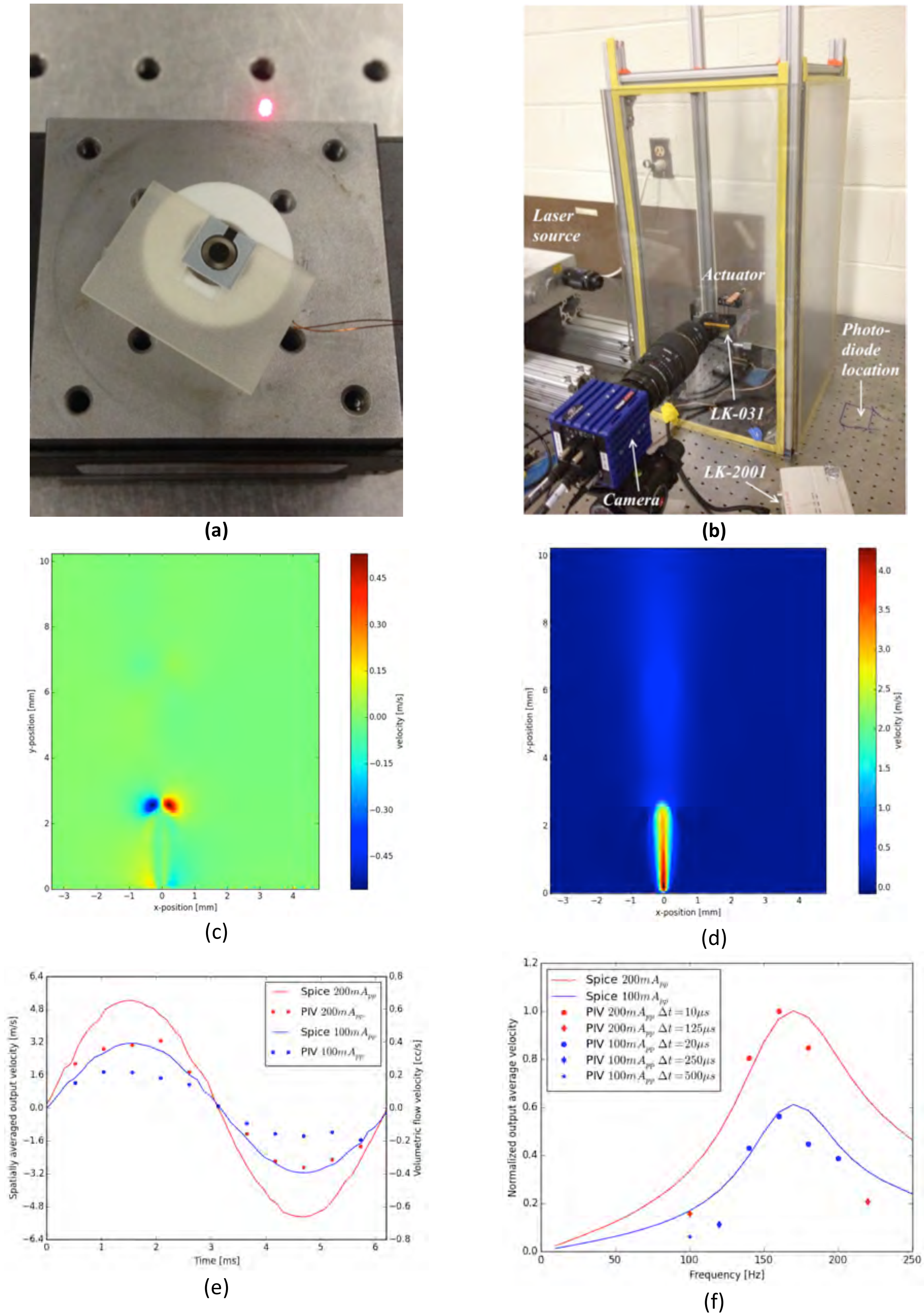

Figure 2: Characterization of the μeZNMF actuator: (a) magnet die in a plastic test jig for diaphragm characterization with a laser displacement sensor, (b) PIV setup for measuring the fluidic output performance of the actuator, (c) PIV horizontal velocity component and (d) vertical velocity component of the actuator's output when operated at 200 mA_{pp} input @ 160 Hz, and (e) output of actuator over one cyle for the same input (LEM and measured) and (d) frequency response of the actuator (LEM and measured).

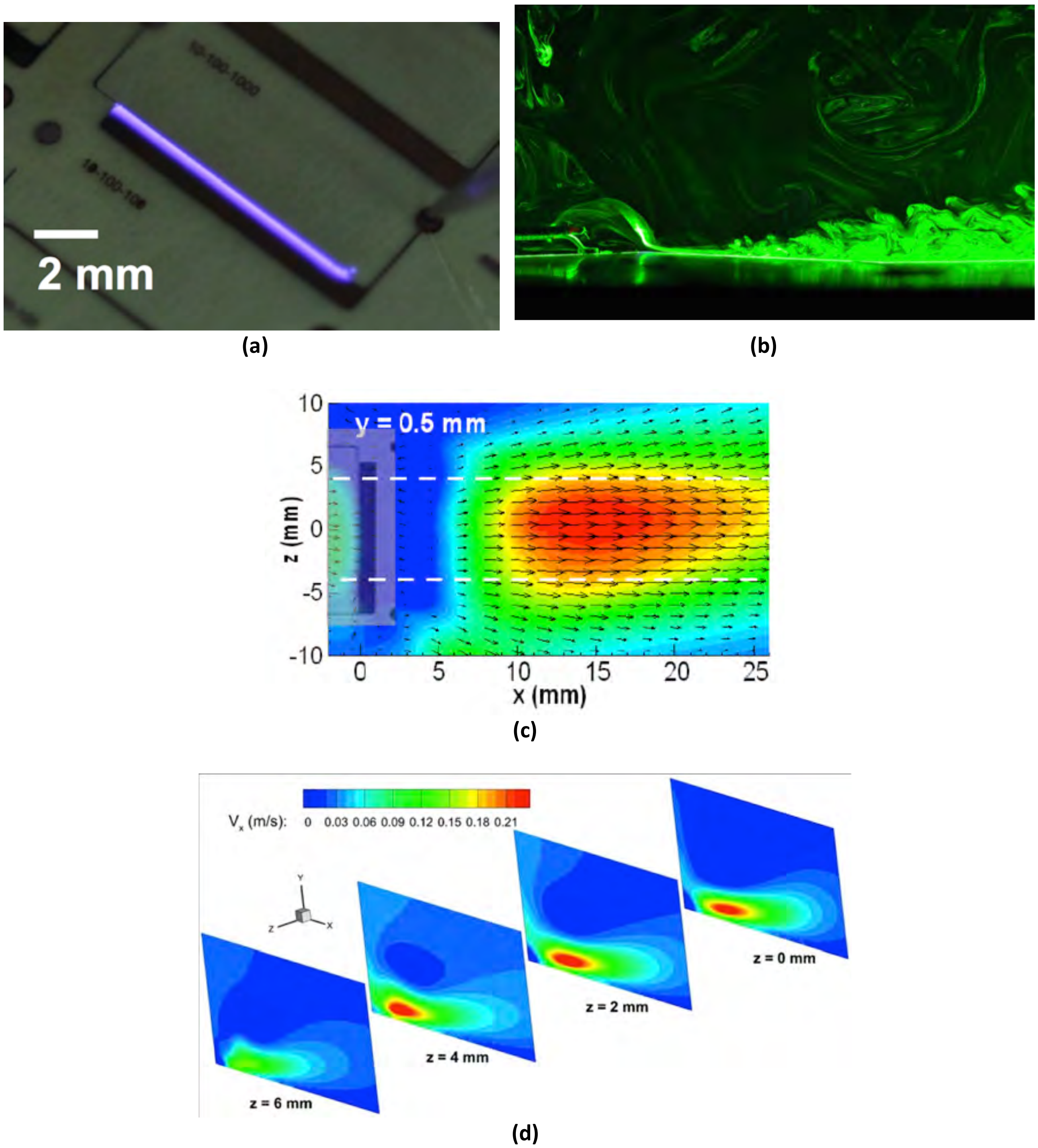

Figure 1: DBS plasma actuators: (a) Top view of an example device in operation, (b) side-view flow visualization of induced flow using a planar laser sheet, (c) 2D particle image velocimetry (PIV) flow measurement depicting the flow seen from the top view (cut at y=0.5 mm; x=0 represents location of actuator), and (d) corresponding flow measurements along the vertical cross-sections spanning across the device, orthogonal to the induce flow.

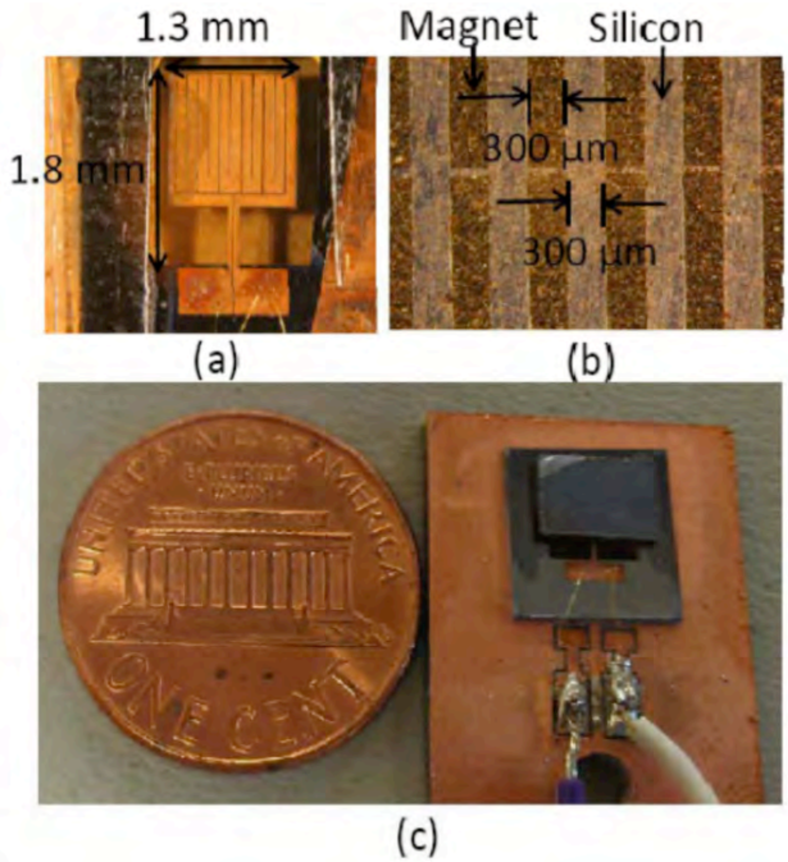

Figure 3: Fully microfabricated vibrational energy harvesting devices relying on electrodynamic transduction: (a) silicon cantilever beam with serpentine copper coil on top, (b) bonded-powder NdFeB micromagnets in silicon trenches, (c) assembled vibrational energy harvester device.

Development of Fully-Integrated Micromagnetic Actuator Technologies
Prof. David P. Arnold, University of Florida

Objective: To transition high-performance micromagnets into fully-integrated, batch-fabricated micromagnetic actuators for Army-specified applications, such as microscale flow-control actuators.

Capstone Accomplishments:

- Batch-microfabricated the smallest known electrodynamically driven synthetic jet actuator (≈ 0.062 cm^3), which demonstrated an output velocity of 4.3 m/s for a 20 mW (200 mA_{pp}) input. (*Figure 1*)
- Developed micro-scale dielectric barrier discharge (DBD) plasma actuators with 10 μm electrodes exhibiting 1.5 m/s output velocity and 1.4 mN/m thrust for power input of 41 W/m of electrode. (*Figure 2*)

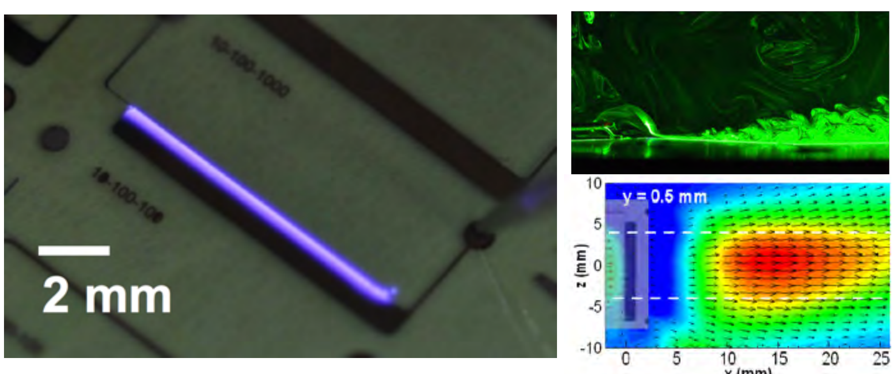

Figure 2: (clockwise from left) (a) top-view of an example device in operation, (b) its flow visualization using a planar sheet laser and (c) PIV flow measurement depicting flow seen from the top view.

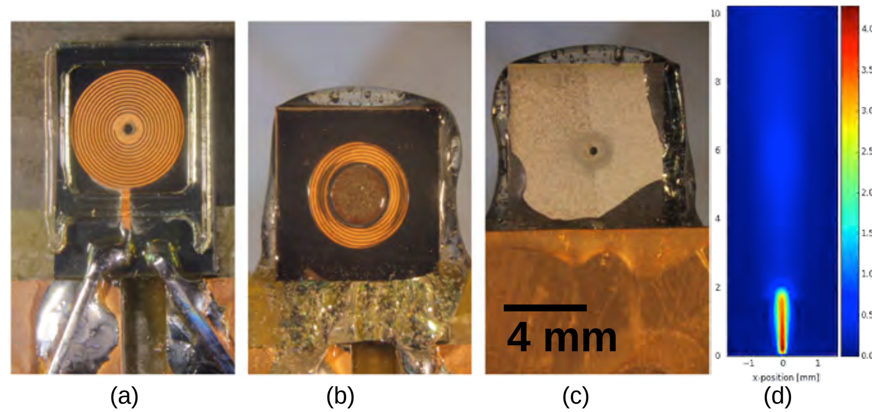

Figure 1: (a) Bottom silicon die 10 mm x 7.5 mm with electroplated and soldered copper microcoil (with a plastic spacer and laser machined orifice), (b) assembled actuator with the silicon die with integrated NdFeB powder micromagnet suspended by a PDMS membrane attached on the coil die, (c) bottom view of the actuator, and (d) PIV output of the actuator from the 160 Hz [the unit for x and y axes is millimeters].

Potential Army Relevance:

- Microscale flow-control actuators can be used for flight-control effectors for micro-UAVs
- Micromagnet technologies have numerous other applications in electronics, microrobotics, biomedical devices, power converters, etc.

Prof. David P. Arnold
University of Florida, Dept. Electrical and Computer Eng.
213 Larsen Hall, Gainesville, FL 32611-6200
Phone: (352) 392-4931 Email: darnold@ufl.edu

Interdisciplinary Microsystems Group
UNIVERSITY OF FLORIDA

UF UNIVERSITY of FLORIDA