AFRL-AFOSR-VA-TR-2016-0353

Energy Harvesting for Soft-Matter Machines and Electronics

Carmel Majidi
CARNEGIE MELLON UNIVERSITY

06/09/2016
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB2
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
27-10-2016

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15 Mar 2013 to 14 Mar 2016

4. TITLE AND SUBTITLE
Energy Harvesting for Soft-Matter Machines and Electronics

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-13-1-0123

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Carmel Majidi

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CARNEGIE MELLON UNIVERSITY
5000 FORBES AVENUE
PITTSBURGH, PA 15213-3815 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB2

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2016-0353

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Air Force (AF) materials capable of dramatic changes in shape and rigidity require soft-matter electronics that support functionality without
interfering with the mechanics of the host structure. In this program, I introduced a new class of soft multifunctional materials that can be used to
power these systems by converting elastic strain energy from large deformations into electricity. These materials are composed of soft elastomers
embedded with a suspension of liquid metal (LM) droplets that control the electrical properties of the composite. Depending on their composition
and microstructure, these LM-embedded elastomers (LMEEs) can be tailored to exhibit exceptionally high electric conductivity, electric
permittivity, and/or thermal conductivity. LMEEs with high permittivity can function as high-k dielectrics for storing and harvesting electrostatic
energy. When integrated with an elastically deformable AF structure, they have the potential to generate electricity as the host structure stretches,
twists, or bends under external loading. This external loading may arise from air drag, wind, ambient vibrations, collisions, etc. and represents
mechanical work that would be otherwise dissipated through damping.

15. SUBJECT TERMS
Energy Harvesting, Soft Microfluidic Generators, Soft-matter Capacitors

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON LEE, BYUNG
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UU		19b. TELEPHONE NUMBER *(Include area code)* 703-696-8483

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

DISTRIBUTION A: Distribution approved for public release.

Carnegie Mellon University

MECHANICAL ENGINEERING

FINAL PERFORMANCE REPORT
Reporting Period: 3/15/2015 – 3/14/2016

Energy Harvesting for Soft-Matter Machines and Electronics (YIP '13)

PI: CARMEL MAJIDI

Mechanical Engineering • Carnegie Mellon University

5000 Forbes Avenue • Pittsburgh, PA 15213
Telephone: (412)268-2492,
E-mail: cmajidi@andrew.cmu.edu
Webpage: http://sml.me.cmu.edu

AFOSR GRANT # FA9550-13-1-0123

Program Manager: Dr. B.L. Lee

May 2016

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
5/25/16	Final Report	3/15/15 to 3/14/16

4. TITLE AND SUBTITLE

Energy Harvesting for Soft-Matter Machines and Electronics (YIP '13)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA9550-13-1-0123

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Carmel Majidi
Associate Professor
Mechanical Engineering
Carnegie Mellon University

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research (AFOSR)
Program: Mechanics of Multifunctional Materials and Microsystems

10. SPONSOR/MONITOR'S ACRONYM(S)

Program Manager: Dr. B.L. Lee

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Air Force (AF) materials capable of dramatic changes in shape and rigidity require soft-matter electronics that support functionality without interfering with the mechanics of the host structure. In this program, I introduced a new class of soft multifunctional materials that can be used to power these systems by converting elastic strain energy from large deformations into electricity. These materials are composed of soft elastomers embedded with a suspension of liquid metal (LM) droplets that control the electrical properties of the composite. Depending on their composition and microstructure, these LM-embedded elastomers (LMEEs) can be tailored to exhibit exceptionally high electric conductivity, electric permittivity, and/or thermal conductivity. LMEEs with high permittivity can function as high-k dielectrics for storing and harvesting electrostatic energy. When integrated with an elastically deformable AF structure, they have the potential to generate electricity as the host structure stretches, twists, or bends under external loading. This external loading may arise from air drag, wind, ambient vibrations, collisions, etc. and represents mechanical work that would be otherwise dissipated through damping. With electrostatic charge recovery using a self-priming circuit, the proposed materials have the potential to exhibit conversion efficiencies (electrical power output / mechanical power input) well above 50%. Moreover, since

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Carmel Majidi
unclassified	unclassified	unclassified		8	19b. TELEPHONE NUMBER *(Include area code)* 412-268-2492

Acknowledgements

The PI and lab members working on this project are grateful for support by the Air Force Office of Scientific Research (AFOSR) through grant FA9550-13-1-0123 with Dr. B.L. Lee as the program manager.

Final Report
Mechanics of Multifunctional Materials & Microsystems

PI: **Carmel Majidi**
Assistant Professor
Department of Mechanical Engineering
Carnegie Mellon University, Pittsburgh, PA 15213
cmajidi@andrew.cmu.edu

Org: Carnegie Institute of Technology
Carnegie Mellon University, Pittsburgh, PA 15213

Grant Title: Energy Harvesting for Soft-Matter Machines and Electronics (YIP '13)

Grant #: FA9550-13-1-0123

Reporting Period: 3/15/15 to 3/14/16

Objectives: Elastically-soft architectures and materials for converting mechanical deformation from vibrations and stretching into electrical energy. Specific tasks include

1. Theoretical modeling of dielectric elastomer generators (DEGs) using nonlinear constitutive laws. [Y1, Y2]
2. Development of soft (0.1-1 MPa) conductive (~10^4 S/m) and high-k (ε_r ~ 10-50) dielectric elastomers. [Y1-Y3]
3. Measurement of electromechanical coupling between stretch and electrical resistivity of conductive elastomers or permittivity of insulating high-k dielectrics; demonstration of vibrational energy harvesting. [Y3]

Y3 Executive Summary

Y3 efforts focused on completing the design and characterization of a new class of soft multifunctional materials for electrostatic energy harvesting. The materials are designed to function as electrodes and dielectrics for an elastically deformable capacitor that changes its stored electrical enthalpy when subject to mechanical loading [Ref. 5]. In this final year of the project, a novel self-priming generator was also introduced. Preliminary measurements obtained with this testbed demonstrate that the soft multifunctional composite can be integrated into an energy harvesting system and has the potential to improve electrical power output.

High-k Dielectric Elastomer

As reported in the previous annual report, the electric properties of soft elastomers can be tailored by adding a suspension of liquid metal (LM) droplets. Depending on their composition, these LM-embedded elastomer (LMEE) can exhibit either high electric conductivity (σ ~ 10^4 S/m; Ref. 2) or permittivity (ε_r ~ 10-50; Ref. 1). Such materials can be used as electrodes and dielectrics, respectively, in a soft-matter capacitive generator that converts mechanical work into electrostatic energy through changes in capacitance and electrical enthalpy. Because the inclusions are liquid phase, these LM-embedded elastomer (LMEE) composites exhibit the same mechanical properties of unfilled rubber – low elastic modulus (0.1-1 MPa), high strain limit (up to 600%), and low mechanical hysteresis. Such properties are required in order for the generator to support large elastic deformations and maximize electrical enthalpy change.

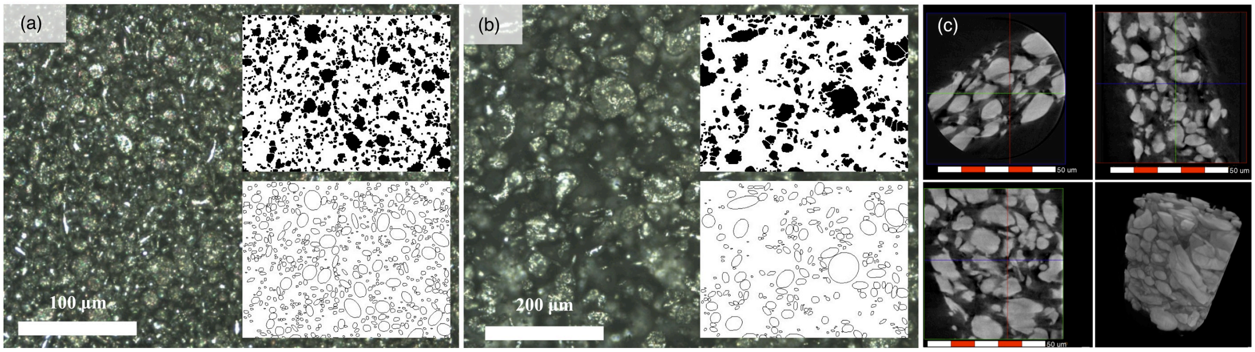

Fig. 1 Optical images of (a) EGaIn-PU (ϕ = 0.5) and (b) EGaIn-PDMS (ϕ = 0.2) composites; insets show results of image processing to identify LM inclusions and estimate dimensions of an ellipsoidal fitting. (c) 3D X-Ray Nano-CT image of a Galinstan-PDMS composite.

The dielectric composites are composed of either polydimethylsiloxane (PDMS) or polyurethane (PU) embedded with a non-percolating suspension of LM microdroplets. Gallium-based alloys such as Ga-In-Sn and Ga-In eutectic (EGaIn) are used as the liquid metal. Referring to the optical and Nano-CT images in **Fig. 1**, the LM suspension is polydisperse and has a random but statistically uniform spatial distribution. Despite the high volume fraction (ϕ) of LM, the droplets do not form a percolating network and instead function as an "artificial dielectric" that significantly increases the effective electric permittivity (ε_r) of the composite. In the case of ϕ = 0.5, ε_r is 4× greater than the permittivity of the unfilled elastomer (ε_m). Measurements of the normalized permittivity $\varepsilon_r/\varepsilon_m$ are plotted in **Fig. 2a**. The solid curve represents a theoretical prediction based on the Maxwell-Garnett effective medium approximation. The strong agreement between the experiment and theory without the aid of data fitting gives compelling evidence for the non-percolating dispersion model of the LM inclusions.

Electromechanical testing is performed using a benchtop LCR meter (BK Precision 889B) that is synchronized with an Instron 5969 tensile tester (**Fig. 2b**). Measurements are performed on a stretchable parallel-plate capacitor composed of a LMEE dielectric and EGaIn electrodes sealed in an additional layer of silicone (figure inset). The capacitance C is observed to increase monotonically with stretch (λ). In the case of pure uniaxial loading ($\lambda_1 = \lambda$, $\lambda_2 = \lambda_3 = \lambda^{-1/2}$), we expect $C/C_0 = \lambda$, where C_0 is the capacitance at 0% strain. However, this appears to overpredict the measured increase, suggesting that either the volumetric permittivity ε_r is decreasing (black markers) or boundary effects are interfering with the transverse stretches. Further testing is required to determine the source of this discrepancy. Lastly, the greatest permittivity is measured with urethane-based LMEEs (**Fig. 2c**), which, like the silicone-based composites, exhibit a low dielectric loss tangent (**Fig. 2d**). The latter suggests that the composites are reliable insulators with negligible leakage over a broad range of frequencies.

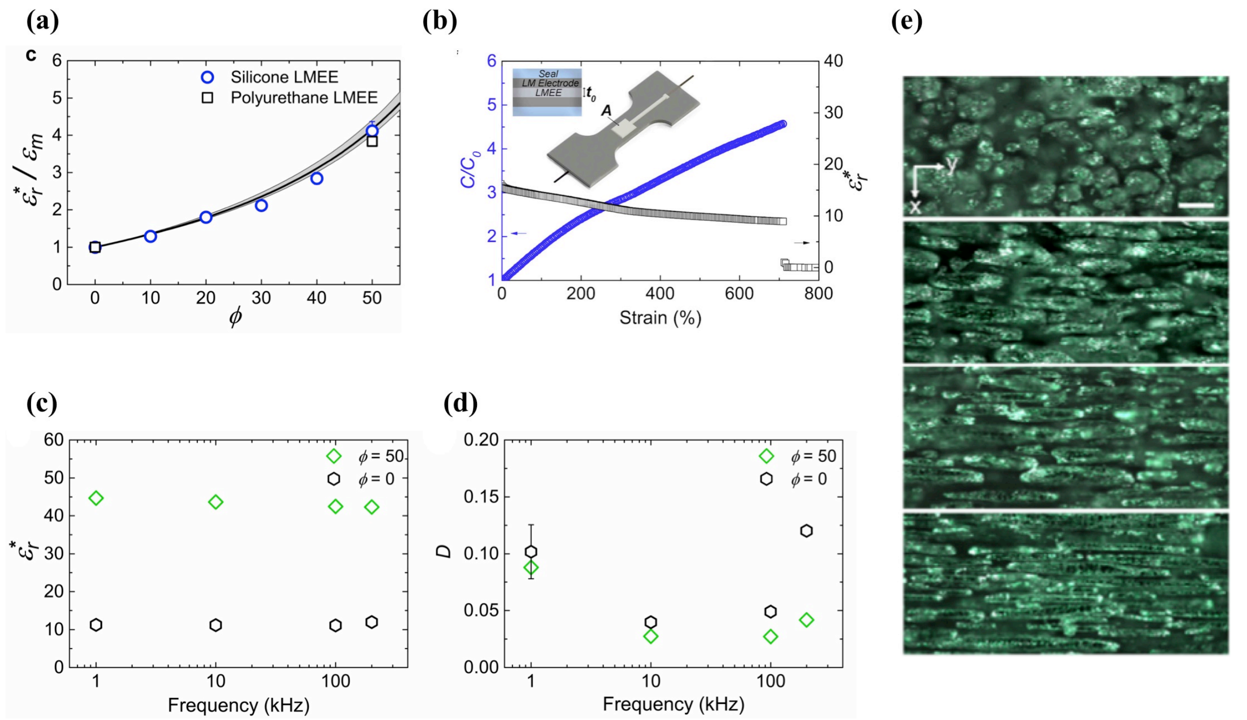

Fig. 2 (a) Plot of relative permittivity versus volume fraction loading of liquid metal (ϕ) in silicone and urethane; the solid curve and shaded bounds correspond to a theoretical prediction based on Equ. (4.2) with an independently measured inclusion aspect ratio of $p = r_3/r_1 = 1.49 \pm 0.36$. (b) Relative change in capacitance of an LMEE dielectric as a function of strain; the black markers correspond to the effective permittivity for a parallel plate capacitor under pure uniaxial load. (c) Plot of dielectric constant as a function of testing frequency for ϕ = 0 and 0.5 showing an increase of over 400% for a filled versus unfilled urethane matrix. (d) Plot of dielectric dissipation factor as a function of testing frequency showing the low dissipation of a urethane-based LMEE. Error bars = ± 1 s.d. and error bars smaller than symbol size are omitted. (e) Images of LM inclusions under strain – from top: 0%, 100%, 200%, 300% (scale bar = 25 μm).

Self-Priming Generator

To demonstrate the ability to harvest energy with an LMEE composite, we developed a self-priming generator testbed (**Fig. 3a**). The testbed is composed of a customized jig for dynamical materials analysis (DMA) and a sample holder for mounting a dielectric elastomer generator (DEG), which are labeled in **Fig. 3b**. Not shown in the figure are the PC interface, data acquisition board, sensor electronics, and self-priming circuit (SPC) for extracting excess electrical charge and priming the DEG. Our customized DMA is a novel design that incorporates a jig saw and Variac to deliver ~1-10 cm linear translational loading at 20-50 Hz frequency. This represents a reliable and inexpensive alternative to conventional DMA systems that allows greater versatility in applying mechanical loads and generating desired motions.

The self-priming circuit (SPC) is based on a design introduced in "Self-Priming Dielectric Elastomer Generators" by McKay, Anderson et al. (*Smart Mater. Struct.* 2015). It contains capacitors and high voltage (HV) diodes configured to manage charge on the surface electrodes as the DEG is cyclically loaded between strained (low voltage, high charge) and relaxed (high voltage, low charge) states. A zener diode is used to limit the maximum voltage on the dielectric and prevent electric breakdown. In parallel with the SPC and DEG is a sensor circuit containing a non-inverting level shifting op-amp and HV probe for measuring the voltage drop across the dielectric.

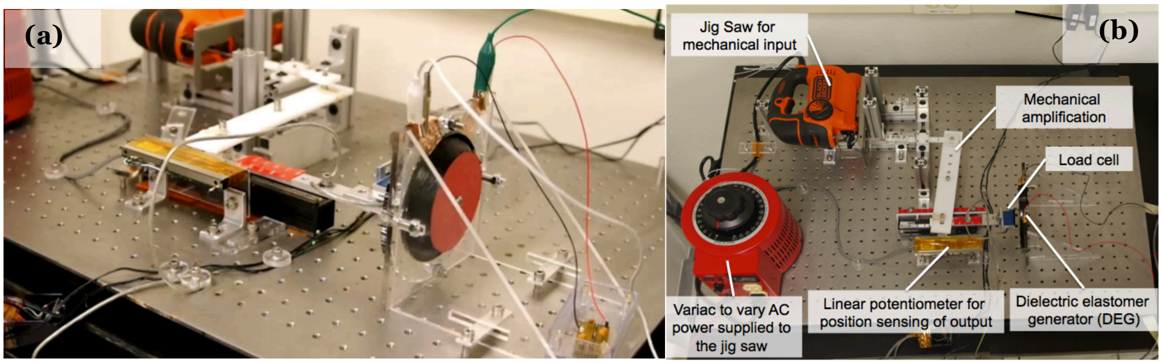

Fig. 3 Dielectric elastomer generator (DEG) testbed. (a) DEG diaphragm being loaded by a jig saw at 50 Hz. (b) Testbed setup composed of dynamical materials analysis (DMA) apparatus. Not shown in the image are the electronics for DEG priming and sensing.

Preliminary measurements obtained with the testbed are presented in **Fig. 4a**. The DEG is composed of an LMEE-PDMS dielectric (ϕ = 0.1) with a carbon grease coating for the electrodes. Mechanical loading is converted into electrostatic energy that scales with the harvested voltage shown in the plot. As shown, the voltage on the DEG exceeds 500V after 45s of cyclical loading. The plot in **Fig. 4b** shows load versus displacement for the DEG. The hysteresis between the loading and unloading corresponds to mechanical damping caused by (i) change in the "Maxwell stress" induced by electrostatic pressure and (ii) viscoelasticity of the dielectric. The area of the hysteresis loop that corresponds to electrostatic damping corresponds to the electrostatic energy generated for each loading cycle.

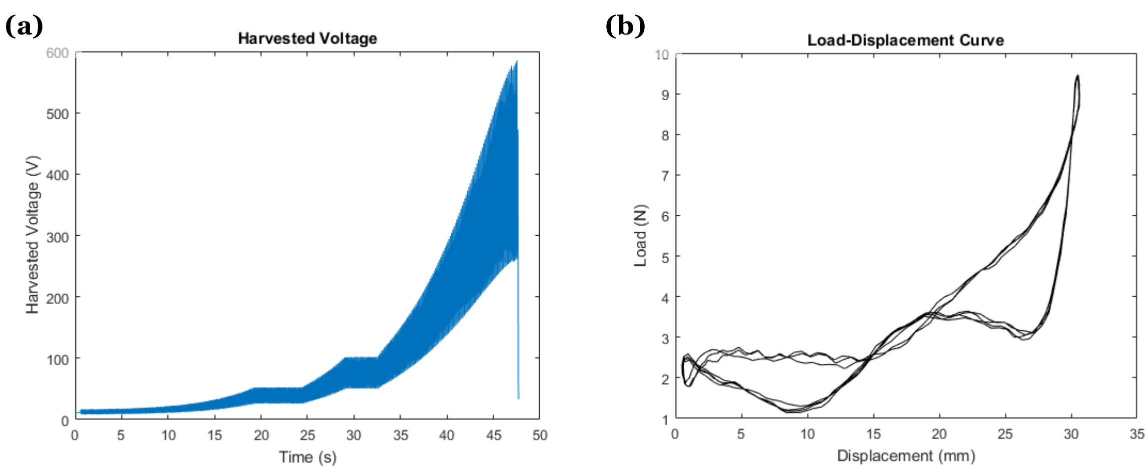

Fig. 4 Dielectric elastomer generator (DEG) testbed. (a) DEG diaphragm being loaded by a jig saw at 20 Hz. (b) Testbed setup composed of dynamical materials analysis (DMA) apparatus. Not shown in the image are the electronics for DEG priming and sensing.

Future Directions

This YIP was successful in introducing a new class of soft multifunctional materials that can be used for energy harvesting. The results presented in Fig. 4 show that LM-embedded elastomer (LMEE) composites can function as a dielectric for converting cyclical mechanical loading into electrostatic energy. In addition to high electric permittivity, LMEEs can also be tailored to exhibit high electrical conductivity (see Y2 annual report). A near-term direction is to also explore enhanced thermal conductivity with LMEEs and examine how processing methods and pre-loading techniques can be used to "program" the shape of the LM inclusions and introduce electrical, thermal, and mechanical anisotropy.

Another future direction is to explore alternative material compositions and structures. This includes co-polymers and surfactants for controlling the size, monodispersity, and spatial distribution of the LM inclusions. Control on LM dispersion has the potential to lead to further improvements in electrical and thermal properties. This is especially true for electric breakdown strength, which scales inversely with inclusion size and is expected to increase with enhanced thermal conductivity.

Publications

[1] M. Bartlett, A. Fassler, N. Kazem, E. Markvicka, P. Mandal, C. Majidi, "Stretchable, high-k dielectric elastomers through liquid metal inclusions," *Advanced Materials* in press (2016).

[2] A. Fassler and C. Majidi, "Liquid-Phase Metal Inclusions for a Conductive Polymer Composite," Advanced Materials, 27: 1928–1932 (2015).

[3] N. Kazem, C. Majidi, C. Maloney, "Gelation And Mechanical Response Of Patchy Rods," *Soft Matter* **11** 7877-7887 (2015).

[4] T. Lu, J. Wissman, Ruthika, C. Majidi, "Soft Anisotropic Conductors as Electric Vias for Ga-Based Liquid Metal Circuits," *ACS Applied Materials & Interfaces* **7** 26923–26929 (2015).

[5] A. Tutcuoglu, C. Majidi, "Energy Harvesting with Stacked Dielectric Elastomer Transducers: Nonlinear Theory, Optimization, and Linearized Scaling Law," *Applied Physics Letters* **105** 241905 (2014).

Patent Provisional

A. Fassler, M. Bartlett, N. Kazem, C. Majidi, "Liquid-Phase Metal Inclusions for a Conductive Polymer Composite," *USPTO*, filed December 2014.

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

cmajidi@andrew.cmu.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

412-268-2492

Organization / Institution name

Carnegie Mellon University

Grant/Contract Title
The full title of the funded effort.

Energy Harvesting for Soft-Matter Machines and Electronics (YIP '13)

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-13-1-0123

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Carmel Majidi

Program Manager
The AFOSR Program Manager currently assigned to the award

Dr. Byung "Les" Lee

Reporting Period Start Date

3/15/13

Reporting Period End Date

3/14/16

Abstract

Air Force (AF) materials capable of dramatic changes in shape and rigidity require soft-matter electronics that support functionality without interfering with the mechanics of the host structure. In this program, I introduced a new class of soft multifunctional materials that can be used to power these systems by converting elastic strain energy from large deformations into electricity. These materials are composed of soft elastomers embedded with a suspension of liquid metal (LM) droplets that control the electrical properties of the composite. Depending on their composition and microstructure, these LM-embedded elastomers (LMEEs) can be tailored to exhibit exceptionally high electric conductivity, electric permittivity, and/or thermal conductivity. LMEEs with high permittivity can function as high-k dielectrics for storing and harvesting electrostatic energy. When integrated with an elastically deformable AF structure, they have the potential to generate electricity as the host structure stretches, twists, or bends under external loading. This external loading may arise from air drag, wind, ambient vibrations, collisions, etc. and represents mechanical work that would be otherwise dissipated through damping. With electrostatic charge recovery using a self-priming circuit, the proposed materials have the potential to exhibit conversion efficiencies (electrical power output / mechanical power input) well above 50%. Moreover, since they are intrinsically soft and stretchable, they will not interfere with the ability of the host AF structure to change shape or elastic rigidity.

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF
The maximum file size for an SF298 is 50MB.

AFD-070820-035.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

2016 final report MAJIDI.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

[1] M. Bartlett, A. Fassler, N. Kazem, E. Markvicka, P. Mandal, C. Majidi, "Stretchable, high-k dielectric elastomers through liquid metal inclusions," Advanced Materials in press (2016).

[2] A. Fassler and C. Majidi, "Liquid-Phase Metal Inclusions for a Conductive Polymer Composite," Advanced Materials, 27: 1928–1932 (2015).

[3] N. Kazem, C. Majidi, C. Maloney, "Gelation And Mechanical Response Of Patchy Rods," Soft Matter 11 7877-7887 (2015).

[4] T. Lu, J. Wissman, Ruthika, C. Majidi, "Soft Anisotropic Conductors as Electric Vias for Ga-Based Liquid Metal Circuits," ACS Applied Materials & Interfaces 7 26923–26929 (2015).

18. New discoveries, inventions, or patent disclosures:
Do you have any discoveries, inventions, or patent disclosures to report for this period?

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

none

Change in AFOSR Program Manager, if any:

none

Extensions granted or milestones slipped, if any:

none

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

May 25, 2016 14:05:53 Success: Email Sent to: cmajidi@andrew.cmu.edu