AFRL-AFOSR-VA-TR-2019-0302

Multifunctional Devices enabled by 4D Hybrid Printing

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08/26/2019
Final Report

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)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
8/22/2019	Final	05/01/2016- 04/30/2019

4. TITLE AND SUBTITLE

Multifunctional Devices enabled by 4D Hybrid Printing

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA9550-16-1-0169

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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Kurt Maute

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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

Georgia Institute of Technology

8. PERFORMING ORGANIZATION REPORT NUMBER

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

Air Force Office of Scientific Research
875 N RANDOLPH ST
ARLINGTON, VA
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11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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Multifunctional composites; functional materials; mechanics; 3D printing; additive manufacturing

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Organization / Institution name

Georgia Institute of Technology

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The full title of the funded effort.

Multifunctional Devices enabled by 4D Hybrid Printing

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-16-1-0169

Principal Investigator Name

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

H. Jerry Qi

Program Officer

The AFOSR Program Officer currently assigned to the award

Dr. Byung Lee

Reporting Period Start Date

05/01/2016

Reporting Period End Date

04/30/2019

Abstract

The goal of this research is to develop a new tightly-integrated digital design and manufacturing paradigm of 4D hybrid printing of robotic composites that can detect and respond to environmental changes by dramatic actions including shape changing and motion via i) directly 4D printed active structures with the precise and optimal layout of multiple active materials, electronics devices, and wires; and ii) field-controllable shape changes and device-driven motions among multiple topological configurations. Our main achievements in this project include: 1) 4D Printing of Active Composites; 2) 4D Printing via Hybrid Printing; 3) Pick-and-place and liquid crystal elastomers for reversible folding structures; 4) 3D printing LCE and LCE fibers; 5) 3D printing highly stretchable and self-healing elastomers; 6) 3D printing novel polymers toward 4D printing using two-stage curing method; 7) Computational design methodology for robotic composites. 19 papers were published

including three in Science Advances, and one invited review paper in Advanced Functional Materials. Our work on direct 4D printing was widely reported by a variety of media, including Scientific America and Discovery Channel, etc.

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2. Yuan, C., Wang, T.J., Dunn, M.L., Qi, H.J., 2017. 3D Printed Active Origami with Complicated Folding Patterns, International Journal of Precision Engineering and Manufacturing-Green Technology, 4:281-289.
3. Liu, K., Wu, J., Paulino, G., QI, H.J., 2017. Programmable Deployment of Tensegrity Structures by Stimulus-Responsive Polymers, Scientific Reports, 7:3511.
4. Ding, Z, Yuan, C., Peng, X., Wang, T., Qi, H.J., Dunn, M., 2017. Direct 4D Printing via Active Composite Materials. Science Advances, 3:e1602890.
5. Yuan, C., Ding, Z., Wang, T.J., Dunn, M.L., Qi, H.J., 2017. Shape forming by thermal expansion mismatch and shape memory locking in polymer/elastomer laminates. Smart Materials and Structures, 26:105027.
6. Ding, Z., Weeger, O., Qi, H.J., Dunn, M.L., 2018. 4D rods: 3D structure via programmable 1D composite rods, Materials & Design, 137, 256-265.
7. Zhao, Z., Wu, J., Mu, X., Chen, H., Qi, H.J., Fang, D., 2017. Origami by Frontal Photopolymerization, Science Advances, 3:e1602326.
8. Yuan, C., Roach, D., Dunn, C., Mu, Q., Kuang, X., Yakacki, C.M., Wang, T.J., Yu, K., Qi, H.J, 2017. 3D printed reversible shape changing soft actuator assisted by liquid crystal elastomer, Soft Matter, 13:33, 5558-5568.
9. Lei, M., Yu, K., Lu, H., Qi, H.J., 2017. Influence of structural relaxation on thermomechanical and shape memory performances of amorphous polymers, Polymer, 109 , 216-228.
10. Zhao, Z., Wu, J., Mu, X., Qi, H.J., Fang, D., 2017. Desolvation induced origami of photocurable polymers by direct light processing, Macromolecular Rapid Communication, available online on 12/22/2016.
11. Mu, Q., Dunn, C., Wang, L., Dunn, M.L., Qi, H.J., Wang, T., 2017. Thermal cure effects on electromechanical properties of conductive wires by direct ink write for 4D printing and soft machines. Smart Materials and Structures, 26, 045008.
12. Mu, Q., Lei, M., Roach, D., Dunn, C., Kuang, X., Wang, T., Qi, H.J., 2018. Intense Pulsed Light Sintering of Thick Conductive Wires on Elastomeric Dark Substrate for Hybrid 3D Printing Applications, Smart Materials and Structures, 27: 115007.
13. Kuang, X., Chen, K., Dunn, C.K., Wu, W., Li, V., and Qi, H.J., 2018. 3D Printing of Highly Stretchable, Shape-Memory and Self-Healing Elastomer toward Novel 4D Printing. ACS Applied Materials & Interfaces, 10:8, 7381-7388.
14. Kuang, X., Zhao, Z., Chen, K., Fang, D., Kang, G., and Qi, H.J., 2018. High Speed 3D Printing of High-performance Thermosetting Polymers via Two-stage Curing. Macromolecular Rapid Communication, 1700809.
15. Chen, K., Kuang, X., Li, V., Kang, G., Qi, H.J., 2018. Fabrication of Tough Epoxy with Shape Memory Effects by UV-

assisted Direct-ink Write Printing. Soft Matter, 14(10), 1879-1886.
16. Roach, D.J., Yuan, C., Kuang, X., Li, V.C., Blake, P., Romero, M.L., Hammel, I., Yu, K., Qi, H.J. 2019. ACS Applied Materials & Interfaces, 11:19514-19521.
17. Roach, D.J., Kuang, X., Yuan, C., Chen, K., QI, H.J., 2019. Novel Ink for Ambient Condition Printing of Liquid Crystal Elastomers for 4D Printing, Smart Materials and Structures, 27:125011.
18. Kuang, X., Wu, J., Chen, K., Zhao, Z., Ding, Z., Hu, F., Ding, Z., Fang, D., Qi, H.J., 2019. Grayscale Digital Light Processing 3D Printing for Highly Functionally Graded Materials, Science Advances. 5(5), eaav 5790.
19. (Invited review) Kuang, X., Roach, D.J., Wu, J., Hamel, C.M., Wang, T. Dunn, M.L., Qi, H.J., 2019. Advance in 4D Printing: Materials and Applications. Advanced Functional Materials, 29(2), 1805290.

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