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Design of Actively Controlled Microarchitectures with Programmable Mechanical Properties

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Final Report

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We have conducted the research necessary to enable the design and fabrication of actively controlled microarchitectures (ACMs). ACMs are a new kind of mechanical metamaterial that utilize flexures, actuators, sensors, and control circuitry within tiny unit cells that constitute large lattices to achieve system-level properties or shape changing capabilities that can be programmed and uploaded on demand.

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Final Report

Design of Actively Controlled Microarchitectures with Programmable Mechanical Properties

PI: Jonathan Hopkins

We have conducted the research necessary to enable the design and fabrication of actively controlled microarchitectures (ACMs). ACMs are a new kind of mechanical metamaterial that utilize flexures, actuators, sensors, and control circuitry within tiny unit cells that constitute large lattices to achieve system-level properties or shape changing capabilities that can be programmed and uploaded on demand. We received an issued patent on this concept [P1] and published a number of papers introducing the idea in the context of different designs [J1-J3, C1,C2] during the course of this grant.

Contributions to the design of ACMs:

Our specific contributions toward enabling the design of ACMs include the following:

1) We extended the core mathematics underlying the freedom, actuation, and constraint topologies (FACT) approach, which PI Hopkins created, to enable the analysis and design of general interconnected hybrid systems (i.e., systems that consist of many bodies interconnected in a truss-like lattice by flexible elements that can't be divided into parallel and serial subsystems) [J4, C3]. Although this theory can be generally applied to any compliant system configuration, it is directly applicable to the design of ACMs that utilize flexure bearings within individual unit cells to guide the motions of the interconnected shuttles. This advance has led to a fundamentally new way to design mechanical metamaterials in general. The papers published on this topic were rewarded with a Best Paper Award at ASME's IDETC mechanisms and robotics conference and a Freudenstein Young Investigator award.
2) More recently, we created a new mathematical theory and incorporated it with the former paper-pencil FACT approach to create an automated version of the FACT approach for rapidly generating the compliant topologies of general mechanical metamaterials including the topologies of ACMs of any kind (e.g., aperiodic designs with no repeating pattern of unit cells). This approach leverages simplified assumptions about the flexible elements that constitute such topologies so that the approach can generate 3D aperiodic topologies with 6 orders of magnitude greater speed than other competing computational approaches. Whereas such approaches (e.g., topology optimization) often require 10s of hours to synthesize a single 2D unit cell within a periodic lattice, our new approach can generate thousands of unique 3D unit cells within 10s of seconds. Thus, we have dramatically improved general metamaterial design tools so that computers can rapidly search the design space without becoming overwhelmed by their complexity. *Nature Communications* recently accepted our breakthrough paper on this topic [J5].
3) We have also extended the mathematics of FACT to enable the synthesis of flexure systems with decoupled actuators [J6]. Although this theory is again applicable to many applications (e.g., precision motion systems), it is directly applicable to shape-morphing ACMs that utilize multiple actuators to drive multiple degrees of freedom to change the material's net shape. By decoupling their actuators, such systems are easier to control and do not require stacked actuator configurations.
4) Whereas the previous three design contributions are all extensions of the FACT approach to enable the synthesis of the topologies of general mechanical metamaterials including ACMs, it was also necessary for us to create a complementary follow-on approach to optimize the

geometry of the topologies generated. We thus created the Boundary Learning Optimization Tool (BLOT) [J7, C4]. This tool generates accurate models of general parameterized metamaterial topologies generated by FACT by training a neural network using a minimal number of automated finite element simulations. It then uses this model in conjunction with adapted versions of the Sequential Quadratic Programming (SQP) and Augmented Lagrangian Pattern Search (ALPS) algorithms to iteratively identify the performance boundary achieved by the design for any number of desired performance capabilities. Using this tool, the topology of any general metamaterial topology can be optimized to achieve the largest ranges of achievable programmable properties. Thus, BLOT completes the last step of the design process for ACMs. We have a provisional patent application on BLOT [P2] and received the Theoretical Contributions in Compliant Mechanisms Award at ASME's IDETC Mechanisms and Robotics Conference for our conference paper on the topic [C4]. We have used BLOT to synthesize numerous ACM topologies generated by our FACT extensions.

Contributions to the fabrication of ACMs:

In addition to fabricating various macro-scale ACM designs, we have pioneered the micro-fabrication of ACMs using a new integrated optical tweezers and two-photon stereolithography fabrication approach. We created and advanced the scanning holographic optical tweezers (SHOT) approach [J8, C5] for dramatically increasing the number of particles that can be simultaneously handled compared with other existing optical-tweezers approaches. We automated the assembly approach of these particles [J9, J10, C6] and simulated the assembly process using advanced molecular dynamic tools to optimize the assembly speed [J11]. We also created a new way to rapidly print 3D arbitrarily-shaped particles as they continuously flow in a stream of photocurable polymer (a.k.a., continuous-flow lithography) [J12] and explored the concept of digital holographic lithography [C7]. Using these advances, we were able to fabricate ACMs that could not be made using any other existing technology and can assemble them at unprecedented speeds. We are also soon to be able to print ACMs directly using multi-material two-photon stereo-lithography with non-conductive polymers and highly conductive silver deposits simultaneously. This will enable the electrical traces to be 3D printed within 10s of micron-sized ACM unit cells. We recently used traditional micro-fabrication technologies to fabricate and collected data from the smallest ACM to date. The preliminary design for the actuator of this ACM was published as a conference paper [C8]. We are soon to submit a journal publication on the final results. We also recently applied our integrated optical tweezers and two-photon stereolithography fabrication approach toward printing structures with embedded strain energy [J13]. The two-photon stereolithography portion of our system prints the initial structures as the optical-tweezers portion of the system deforms the structures printed to create metamaterials that are not possible to make using any other approach.

Other related research topics pursued:

A number of other related research topics arose from this grant beyond what was initially proposed. As we studied ACMs that achieve programable shape-morphing capabilities, we advanced large deformation metamaterial design theory [J14] and pursued alternative approaches for achieving shape reconfiguration in general. One approach utilizes rigid micro-cams joined together by flexure straps that guide their rolling motions to achieve dramatic shape deformations [J15]. Another approach utilizes flexure elements that buckle to achieve multi-stable bulk shape changes [J16, C9]. We have a provisional patent application on the latter approach [P3]. Finally, we pursued other more passive ways to achieve programmable properties and computation beyond the active approaches originally proposed. We created a functionally complete library of flexure-based mechanical logic gates [J17] that can be strung together to generate new materials that can mechanically perform calculations in extreme environments, which would otherwise destroy traditional electronic chips. We recently filed for a patent on the idea [P4]. Awards and honors of note received during the duration of this grant are reported in the last section. Many of these awards were received as a direct result of the work conducted for this work.

References generated under this grant:

Journal Publications

[J1] Song, Y., Dohm, P.C., Haghpanah, B., Vaziri, A., **Hopkins, J.B.**, 2016, "An Active Microarchitectured Material that Utilizes Piezo Actuators to Achieve Programmable Properties," *Advanced Engineering Materials*, 18(7): pp. 113-1117.

[J2] Shaw, L.A., **Hopkins, J.B.**, 2015, "An Actively Controlled Shape-morphing Compliant Microarchitectured Material," *Journal of Mechanisms and Robotics*, 8(2): 021019 (10 pages).

[J3] Haghpanah, B., Ebrahimi, H., Mousanezhad, D., Hamouda, A.M.S., **Hopkins, J.B.**, Vaziri, A., 2016, "Programmable Elastic Metamaterials," *Advanced Engineering Materials*, 18(4): pp. 643-649.

[J4] Sun, F., **Hopkins, J.B.**, 2017, "Mobility and Constraint Analysis of Interconnected Hybrid Flexure Systems via Screw Algebra and Graph Theory," *Journal of Mechanisms and Robotics*, 9(3): 031018 (12 pages).

[J5] Shaw, L.A., Sun, F., Portela, C.M., Barranco, R.I., Greer, J.R., **Hopkins, J.B.**, "Computationally Efficient Design of Directionally Compliant Metamaterials," **accepted** to *Nature Communications*, November 2018

[J6] Hopkins, J.B., McCalib Jr., D., 2016, "Synthesizing Multi-axis Flexure Systems with Decoupled Actuators," *Precision Engineering*, 46: pp. 206-220

[J7] Hatamizadeh, A., Song, Y., **Hopkins, J.B.**, 2018, "Optimizing the Geometry of Flexure System Topologies Using the Boundary Learning Optimization Tool (BLOT)," *Mathematical Problems in Engineering*, Volume 2018, Article ID 1058732, (14 pages)

[J8] Shaw, L.A., Panas, R.M., Spadaccini, C.M., **Hopkins, J.B.**, 2017, "Scanning Holographic Optical Tweezers," *Optics Letters*, 42(15): pp. 2862-2865 (highlighted on the journal's website as the editor's pick)

[J9] Shaw, L.A., Chizari, S., **Hopkins, J.B.**, 2018, "Improving the Throughput of Automated Holographic Optical Tweezers," *Applied Optics*, 57(22): pp. 6396-6402

[J10] Shaw, L.A., Chizari, S., Panas, R.M., Shusteff, M., Spadaccini, C.M., **Hopkins, J.B.**, 2016, "Holographic Optical Assembly and Photopolymerized Joining of Planar Microspheres," *Optics Letters*, 41(15): pp. 3571-3574

[J11] Porter, M.D., Giera, B., Panas, R.M., Shaw, L.A., Shusteff, M., **Hopkins, J.B.**, 2018, "Experimental Characterization and Modeling of Optical Tweezer Particle Handling Dynamics," *Applied Optics,* 57(22): pp. 6565-6571

[J12] Shaw, L.A., Chizari, S., Shusteff, M., Naghshi-Nilchi, H., Di Carlo, D., **Hopkins, J.B.**, 2018, "Scanning Two-photon Continuous Flow Lithography for Synthesis of High-resolution 3D Microparticles," *Optics Express*, 26(10): pp. 13543-13548

[J13] Chizari, S., Shaw, L.A., **Hopkins, J.B.**, 2018, "Simultaneous Printing and Deformation of Microsystems via Two-Photon Lithography and Holographic Optical Tweezers," *Materials Horizons*, DOI: 10.1039/c8mh01100a

[J14] Delissen, A., Radaelli, G., Shaw, L.A., **Hopkins, J.B.**, Herder, J.L., 2018, "Design of an Isotropic Metamaterial with Constant Stiffness and Zero Poisson's Ratio over Large Deformations," *Journal of Mechanical Design*, 140(11): 111405 (10 pages)

[J15] Shaw, L.A., Chizari, S., Dotson, M.B., Song, Y., **Hopkins, J.B.**, 2018, "Compliant Rolling-contact Architected Materials for Shape Reconfigurability," *Nature Communications*, 9: 4594 (12 pages)

[J16] Haghpanah, B., Salari-Sharif, L., Pourrajab, P., **Hopkins, J.B.**, Valdevit, L., 2016, "Multistable Shape-Reconfigurable Architected Materials," *Advanced Materials*, 28(36): pp. 7915-7920 (an image of the research is featured on the inside back cover of the *Advanced Materials* issue and the research was also highlighted in *Nature*, 535: pp. 327 and was featured on the cover of *Nature Reviews Materials* 2(11) November 2017)

[J17] Song, Y., Panas, R.M., Chizari, S., Shaw, L.A., Mancini, J.A., **Hopkins, J.B.**, Pascall, A.J., "Additively Manufacturable Micro-Mechanical Logic Gates," **accepted** to *Nature Communications*, November 2018

Conference Papers

[C1] Hopkins, J.B., "Flexure Design of Active Microarchitectured Materials That Achieve Programmable Properties via Control," *Proc. of the 30th Annual Meeting of the American Society for Precision Engineering*, Austin, TX, November 2015.

[C2] Shaw, L.A., **Hopkins, J.B.**, "A Shape-controlled Compliant Microarchitectured Material," *Proc. of the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE*, Boston, MA, August 2015.

[C3] Sun, F., **Hopkins, J.B.**, "Mobility Analysis of Interconnected Hybrid Flexure Systems Using Screw Algebra and Graph Theory," *Proc. of the American Society of Mechanical Engineers (ASME) International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (IDETC/CIE), Charlotte, NC, August 2016.

[C4] Hatamizadeh, A., Song, Y., **Hopkins, J.B.**, "Geometry Optimization of Flexure System Topologies Using the Boundary Learning Optimization Tool (BLOT)," *Proc. of the American Society of Mechanical Engineers (ASME) International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)*, Cleveland, OH, August 2017

[C5] Shaw, L.A., Chizari, S., Parker, D., Panas, R.M., Shusteff, M., Spadaccini, C.M., **Hopkins, J.B.**, "Additive Fabrication and Micro-Assembly with Scanning Holography," *Proc. of the 31st Annual Meeting of the American Society for Precision Engineering (ASPE)*, Portland, OR, October 2016.

[C6] Shaw, L.A., Chizari, S., Austin, S., **Hopkins, J.B.**, "Automated Assembly with Optical Tweezers," *Proc. of the 32nd Annual Meeting of the American Society for Precision Engineering (ASPE)*, Charlotte, NC, October 2017

[C7] Shusteff, M., Dudoff, J.K., Browar, A.E.M., Shaw, L.A., Panas, R.M., **Hopkins, J.B.**, Fang, N.X., Spadaccini, C.M., "Optimal Source Beam Shaping for Digital Holographic Lithography," *Proc. of The Optical Society (OSA) Digital Holography and 3-D Imaging (DH) conference*, Heidelberg, Germany, July 2016.

[C8] Zhao, C., Ladner, I.S., Song, Y., **Hopkins, J.B.**, Cullinan, M.A., "Design and Modeling of a Bidirectional Thermal Actuator," *Proc. of the 32nd Annual Meeting of the American Society for Precision Engineering (ASPE)*, Charlotte, NC, October 2017

[C9] Haghpanah, B., Pourrajab, P., Salari-Sharif, L., **Hopkins, J.B.**, Valdevit, L., "Two-dimensional Shape Re-configurable Architectured Materials," *Proc. of the 11th International Conference on Micro Manufacturing ICOMM*, Orange County, CA, March 2016.

Patents Issued

[P1] US 10065322 B2: "Actively Controlled Microarchitectures with Programmable Bulk Material Properties," **Hopkins, J.B.**, Song, Y., assigned to The Regents of the University of California, September 2018

Provisional Patent Applications

[P2] "Apparatus and Method for Boundary Learning Optimization," Hatamizadeh, A., Song, Y., **Hopkins, J.B.**, assigned to The Regents of the University of California, July 2017

[P3] "Shape Reconfigurable Materials and Structures for Shape Morphing, Energy Absorption and Tunable Phononic Response," Haghpanah, B., Valdevit, L., **Hopkins, J.B.**, assigned to The Regents of the University of California, March 2016

Invention Disclosures Filed

[P4] IL-13317 "Systems for Mechanical Logic Based on Additively Manufacturable Micro-Mechanical Logic Gates," Song, Y., Panas, R.M., Pascal, A., **Hopkins, J.B.**, assigned to Lawrence Livermore National Security LLC, June 2018

Awards and honors received during the grant period:

V.M. Watanabe Excellence in Research Award, $2,200 received at the 2018 University of California, Los Angeles (UCLA) Henry Samueli School of Engineering and Applied Science Awards Dinner for having demonstrated innovation in pursuing critical research, Los Angeles, CA—03/18

Theoretical Contributions in Compliant Mechanisms Award, $500 received at the *American Society of Mechanical Engineers (ASME) Mechanisms and Robotics Conference* in the *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)* for a paper titled, "Geometry Optimization of Flexure System Topologies Using the Boundary Learning Optimization Tool," Cleveland, OH—08/17

Northrop Grumman Excellence in Teaching Award, $5,000 received at the 2017 University of California, Los Angeles (UCLA) Henry Samueli School of Engineering and Applied Science Awards Dinner for having demonstrated a record of offering students the best possible engineering education through innovative and inspirational teaching methods, curriculum development and support of student academic efforts, Los Angeles, CA—02/17

2016 Freudenstein/General Motors Young Investigator Award, $1,000 received at the *American Society of Mechanical Engineers (ASME) Mechanisms and Robotics Conference* in the *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)* for a paper titled, "Mobility Analysis of Interconnected Hybrid Flexure Systems Using Screw Algebra and Graph Theory," Charlotte, NC—08/16

Best Paper Award Honorable Mention, received at the *American Society of Mechanical Engineers (ASME) Mechanisms and Robotics Conference* in the *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)* for a paper titled, "Mobility Analysis of Interconnected Hybrid Flexure Systems Using Screw Algebra and Graph Theory," Charlotte, NC—08/16

Presidential Early Career Award for Scientists and Engineers (PECASE), $250,000 received from the Department of Energy's (DOE) National Nuclear Security Administration (NNSA) and honored by President Barack Obama at the White House. This award is the highest honor bestowed by the United States Government on science and engineering professionals in the early stages of their independent research careers, Washington, D.C.—05/16

Poster Competition Winner, $250 received at the UCLA MAE Department Research Open House in conjunction with the Annual Industrial Advisory Board (IAB) Meeting for a poster titled, "Microfabrication with Holographic Optical Tweezers," Los Angeles, CA—02/16

Best Fast Forward Presentation Award, received at the Compliant Mechanisms and Micro/Nano Mechanisms A. Midha Symposium of the *American Society of Mechanical Engineers (ASME) International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)* for a paper titled, "A Shape-controlled Compliant Microarchitectured Material," Boston, MA—08/15