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Mechanical Neural-network Architecture Materials that Learn

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that can learn to optimally change their shape and stiffness at select locations as flight conditions change, (ii) aircraft exteriors that can learn to compensate for damage that may occur during combat by maintaining their designed properties regardless of defects or wear, and (iii) precision components within an aircraft that cannot be made of zero-thermal-expansion-coefficient materials but can learn to maintain their shape regardless of fluctuating temperatures.

Final Report:

Mechanical Neural-network Architected Materials that Learn

Abstract

The objective of this research is to apply the concept of artificial neural networks to enable the creation of a new kind of architected material called mechanical neural-network (MNN) architected materials that can learn desired properties via a complex web of active flexible elements (AFE) that constitute the materials' microstructure. Although significant research has been conducted toward enabling advanced materials that utilize active elements to achieve programmable properties, many scenarios exist where a material's environment may change and it is necessary that the material can autonomously adapt its properties accordingly to successfully fulfill its desired purpose. In such scenarios, designers rarely have the time or knowledge of each environmental change to program and upload new control instructions to change the properties as required. Thus, it is necessary that the material can learn to change its properties on its own. The research approach was threefold: (1) MNN lattices of various sizes and configurations were designed and simulated to computationally determine the fundamental principles that govern how mechanical networks can learn desired properties. (2) 2D macro- and micro-scale lattices were designed, fabricated, and tested to validate the simulations and demonstrate MNN learning of planar designs on different scales. (3) Research was conducted to enable the fabrication of 3D MNN lattices at their intended micro-scale using a new optical-tweezers-based approach. Example MNN applications include: (i) wings that can learn to optimally change their shape and stiffness at select locations as flight conditions change, (ii) aircraft exteriors that can learn to compensate for damage that may occur during combat by maintaining their designed properties regardless of defects or wear, and (iii) precision components within an aircraft that cannot be made of zero-thermal-expansion-coefficient materials but can learn to maintain their shape regardless of fluctuating temperatures.

Accomplishments

Research Objectives: The objective of this research is to apply the concept of artificial neural networks (ANNs) to enable the creation of a new kind of architected material that can learn desired properties via a complex web of active flexible elements (AFE) that constitute the materials' microstructure.

Goals and tasks:

- (1) ***Design and Simulation:*** Our first goal was to search the full design space of promising AFE designs and optimize their geometries such that they best facilitate MNNs learning. We intended to then simulate a variety of differently sized and configured MNN lattices consisting of these optimized AFE designs to computationally determine the fundamental principles that govern the ability to mechanically learn desired properties and behaviors.

- (2) **2D Validation:** Our second goal was to apply the lessons learned from the simulation task to design and then fabricate two-dimensional (2D) macro-and micro-scale lattices that would be tested to validate the simulations and demonstrate MNN learning of planar designs on different scales.
- (3) **3D Micro-scale Fabrication:** Our third goal was to conduct the research necessary to fabricate three-dimensional (3D) MNN-lattice designs at their intended micro-scale to achieve enhanced learning due to the drastically increased number of AFE connections, which are made possible by 3D lattice topologies.

Accomplished:

All three goals were accomplished as proposed ahead of schedule. Additionally other unanticipated research directions were pursued including (i) mechanical logic approaches for performing mechanical learning, (ii) metamaterials that sequentially deform to achieve mechanical learning, (iii) metamaterials that leverage phase changes to achieve programmable stiffness, and (iv) approaches for designing metamaterials that achieve directions of desired compliance.

Detailed Accomplishments:

- (1) **Design and Simulation:** We extended our freedom and constraint topologies (FACT) approach and our boundary learning optimization tool (BLOT) so that the most promising macro and micro-sized AFEs could be designed. The best macro-scale examples are shown in Fig. 1A-D and the best micro-scale examples are shown in Fig. 1E-F. We performed numerous simulations of many different MNN lattice scenarios using the best of these AFE designs to learn about mechanical learning. Scenarios included, MNNs with AFE's that achieve binary or continuous stiffness changing capabilities, MNNs of different rows, layers, and sizes, MNNs of different packing configurations (square, and triangular), and MNNs that are required to learn different numbers of randomly generated behaviors. Many of these simulations required more than a year to generate the required plots using UCLA's Hoffman supercomputer. The plots are soon to be published in:

[Lee, R., Mulder, E.A.B., Hopkins, J.B., "Mechanical Neural Networks: Architected Materials that Learn Behaviors," submitted to *Science Robotics*, April 2022.](#)

Example simulated lattice results are provided in Fig. 2.

- (2) **2D Validation:** We selected the best AFE designs and built lattices to demonstrate mechanical learning. The first lattice used the AFE design of Fig. 1B and is shown in Fig. 3A-B. We were not able to use this lattice to mechanically learn behaviors due largely to issues pertaining to repeatability and hysteresis. After learning from our failure, we then successfully demonstrated mechanical learning using the design of Fig. 1C as shown in Fig. 3C-D. The design was calibrated and used to demonstrate mechanical learning of two behaviors simultaneously with its AFE's programmed to achieve linear and nonlinear stiffness values. Different learning algorithms were also compared using the lattice of Fig. 3C-D. The results of these experimental studies are summarized in:

[Lee, R., Mulder, E.A.B., Hopkins, J.B., "Mechanical Neural Networks: Architected Materials that Learn Behaviors," submitted to *Science Robotics*, April 2022.](#)

A 3D micro-scale lattice was also successfully fabricated using the design of Fig. 1E as shown in Fig. 4.

- (3) **3D Micro-scale Fabrication:** We advanced our microfabrication capabilities to enable the fabrication of micro-sized MNNs. Specifically, we advanced our hybrid optical-tweezers and two-photon-lithography system so that microspheres could be rapidly assembled and glued together within arbitrary crystal lattices (Fig. 5A). We also enabled the simultaneous printing and manipulation of what is printed using our system (Fig. 5B). We also created and advanced single-material (Fig. 5C) and multi-material (Fig. 5D) continuous flow lithography. Finally, we enabled multi-material two-photon lithography 3D printing (Fig. 5E). These capabilities were critical to pioneer before active MNNs can be fabricated at the micro and nano-scale.
- (4) **Extra Research not Proposed:** We also pursued other relevant efforts under this grant beyond what was proposed. These accomplishments are described in detail in the following papers:
- Farzaneh, A., Pawar, N., Portela, C.M., Hopkins, J.B., 2022, “Sequential Metamaterials with Alternating Poisson’s Ratios,” *Nature Communications*, 13(1): 1041 (9 pages).
 - Panas, R.M., Sun, F., Bekker, L., Hopkins, J.B., 2021, “Combining Cross-pivot Flexures to Generate Improved Kinematically Equivalent Flexure Systems,” *Precision Engineering*, 72: pp. 237-249
 - Kuppens, P.R., Bessa, M.A., Herder, J.L., Hopkins, J.B., 2021, “Compliant Mechanisms that Use Static Balancing to Achieve Dramatically Different States of Stiffness,” *Journal of Mechanisms and Robotics*, 13(2): 021010 (6 pages)
 - Poon, R., Hopkins, J.B., 2019, “Phase-changing Metamaterial Capable of Variable Stiffness and Shape Morphing,” *Advanced Engineering Materials*, 21(12): 1900802 (5 pages) (selected by the editor to be featured in Advanced Science News)
 - Song, Y., Panas, R.M., Chizari, S., Shaw, L.A., Mancini, J.A., Hopkins, J.B., Pascall, A.J., 2019, “Additively Manufacturable Micro-Mechanical Logic Gates,” *Nature Communications*, 10(1): 882 (6 pages) (selected by the editor to be featured in Nature Communications’ Additive Manufacturing and 3D Printing Collection)
 - Shaw, L.A., Sun, F., Portela, C.M., Barranco, R.I., Greer, J.R., Hopkins, J.B., 2019, “Computationally Efficient Design of Directionally Compliant Metamaterials,” *Nature Communications*, 10(1): 291 (13 pages)

Dissemination:

In addition to the journal articles, conference proceedings, and patents published under this grant, the results of this grant were widely disseminated at a variety of conferences (e.g., ASME’s IDETC and ASPE), seminars, workshops, tutorials, and invited talks. Some of the material was also featured on my YouTube Channel, “The FACTs of Mechanical Design,” to reach a broader audience for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

Impacts

Development of the principal discipline(s) of the project:

The knowledge generated lays the foundation for a new field of artificial intelligent (AI) materials that learn their properties and behaviors. The process of mechanical learning in general was investigated and numerous principles were learned of great value to the new field. These principles will enable applications including: (i) aircraft wings that can learn to optimally change their shape

and stiffness at select locations as flight conditions change, *(ii)* aircraft exteriors that can learn to compensate for damage that may occur during combat or overuse by maintaining their designed properties regardless of defects or wear, and *(iii)* electrical, optical, or other components within aircraft that cannot be made of zero-thermal-expansion-coefficient materials but can learn to maintain their shape regardless of fluctuating temperatures.

Other disciplines:

The results of this grant also impact other fields beyond AI materials. Such fields include artificial intelligence, optical tweezing, two-photon lithography, passive metamaterials, and variable stiffness mechanisms.

Describe the impact in this reporting period on the development of human resources

This project provided research opportunities for three graduate students and a number of volunteer undergraduates. The group of students that had the opportunity to work on the grant were from diverse backgrounds. The grant afforded them the opportunity to attend conferences and present their research in this area.

Describe the impact on teaching and educational experiences

This project helped produce content that I was able to teach in a graduate course at UCLA and it was featured in my YouTube channel, “The FACTs of Mechanical Design.” CAD models for some of the designs were posted to Thingiverse.com and have been used by numerous individuals worldwide.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.

This project generated numerous machines for our lab that will be used by future researchers. It produced a working MNN, which will be used by a future student to study the topic further. It also helped advance my group’s hybrid optical-tweezer and two-photon-lithography system, which will also be used by future students to conduct further research.

Impact on society beyond science and technology:

My YouTube Channel has already broadly disseminated some of the designs (some videos have received over 100K views) and future videos will be posted once the bulk content of the grant is published to disseminate the research further.

Changes

There were no changes made to the grant. All the proposed tasks and milestones were completed on time.

Technical Updates

This section provides this report’s figures.

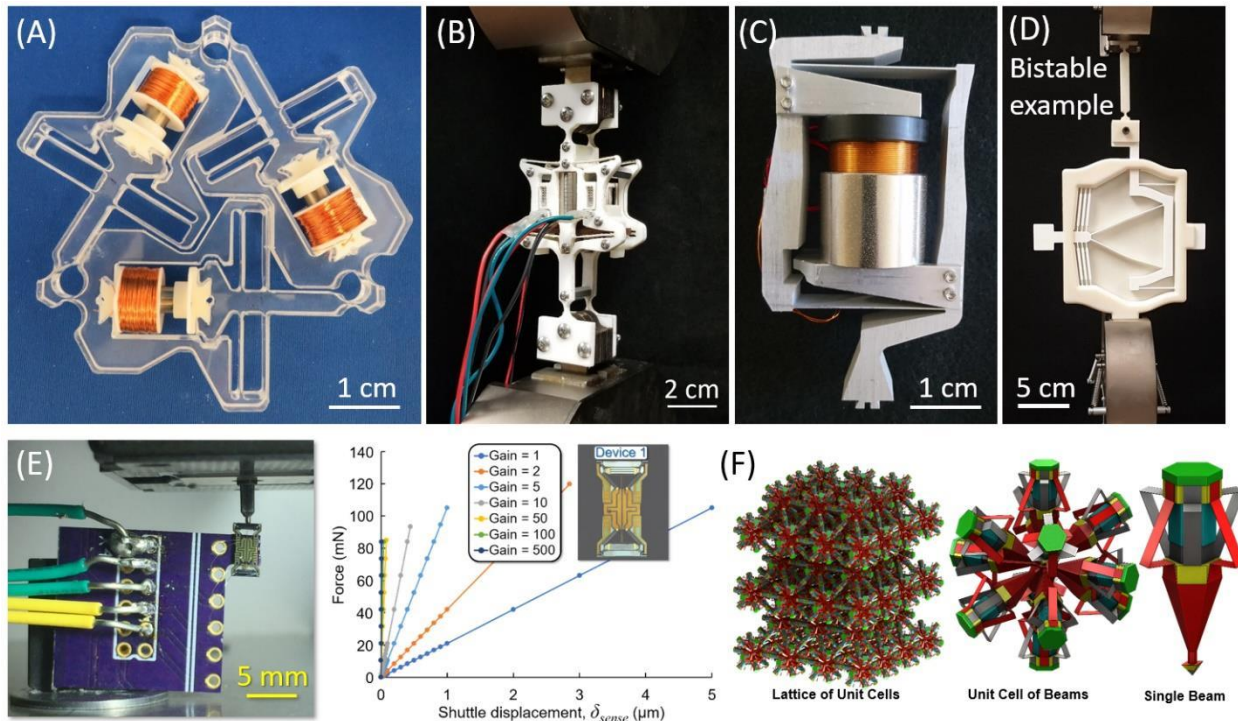


Figure 1. (A)-(D) Macro-scale active flexible elements (AFE) examples. (E)-(F) Micro-scale AFE examples.

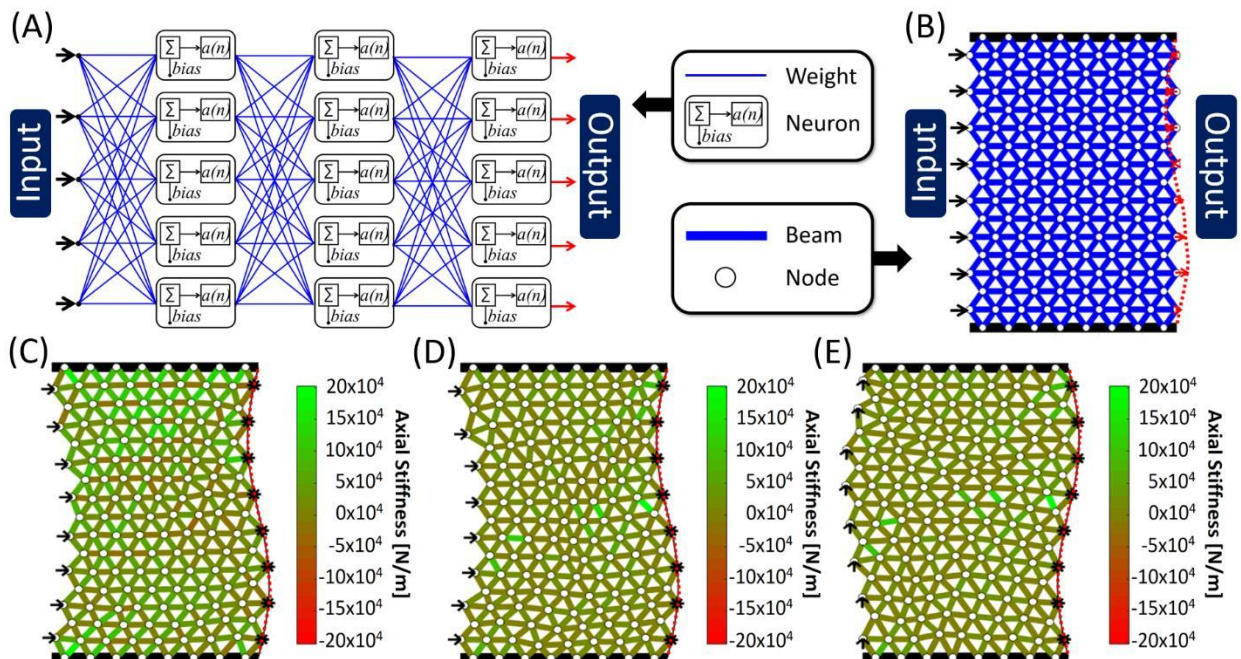


Figure 2. (A) Artificial neural networks are analogous to (B) mechanical neural networks (MNN). (C)-(E) Simulated results of an 8x8 triangular MNN lattice learning sinusoidal shape-morphing behaviors.

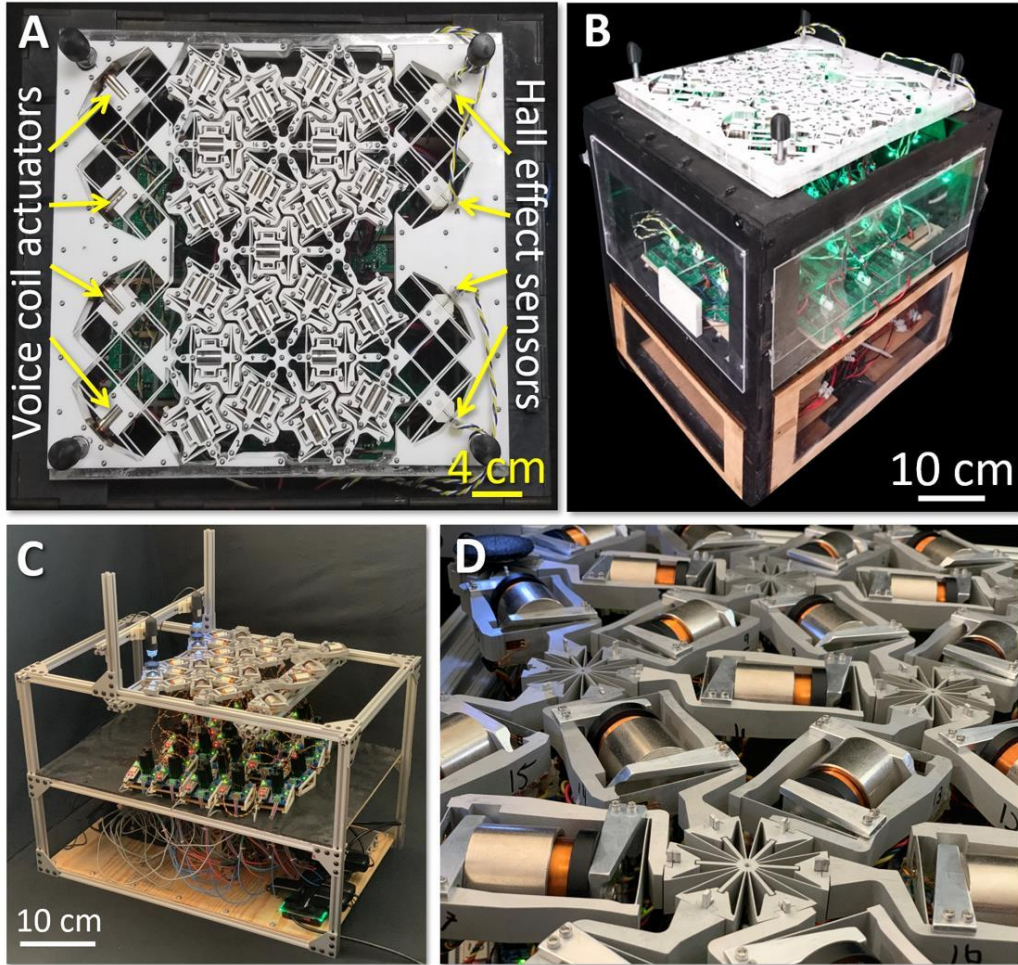


Figure 3. (A)-(B) Our first attempt at demonstrating mechanical learning using a mechanical neural network (MNN), which failed to learn due to hysteresis. (C)-(D) Our second attempt at demonstrating mechanical learning using a MNN, which successfully learned behaviors.

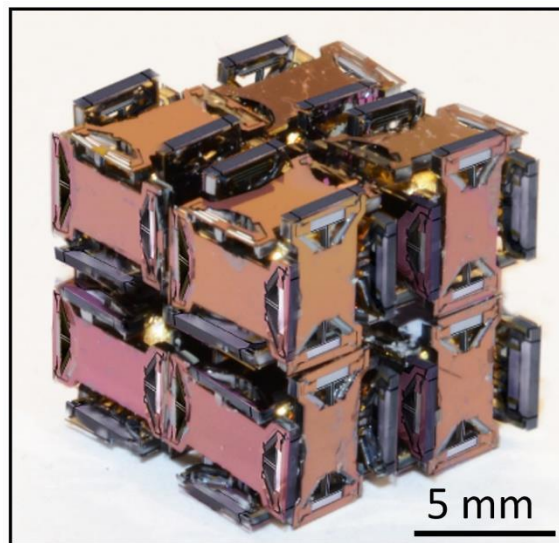


Figure 4. A 3D micro-scale mechanical neural network.

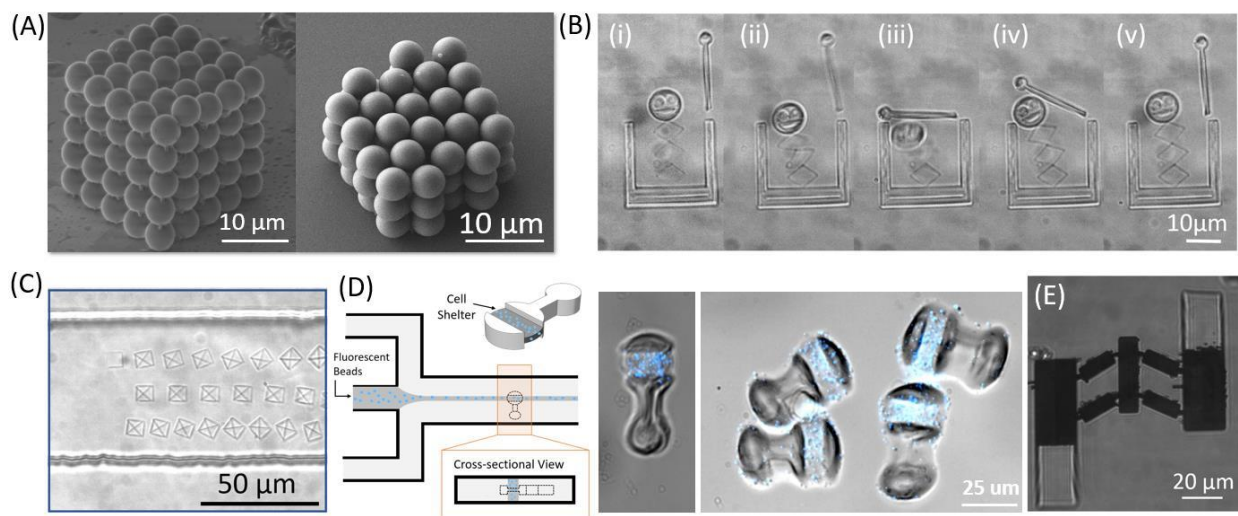


Figure 5. (A) Microgranular crystals of different packing configurations assembled using optical tweezers. (B) A jack-in-the-box printed via two-photon lithography, which is also manipulated and deformed using optical tweezers as it is printed. (C) Many squares with x's in their center are rapidly printed in a micro-channel as the photocurable polymer continuously flows. (D) A similar continuous flow lithography demonstration showing that multi-material particles can be printed at the intersection of coflowing streams of different photocurable polymers. (E) Two-photon lithography being used to 3D print multi-material structures using both a conductive (silver, shown black) and nonconductive (polymer) material simultaneously.