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BIFURCATION-BASED ACTUATION FOR AUTONOMOUS, SMART STRUCTURES

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14. ABSTRACT
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(Aim 1, Stimuli-responsive materials.) The primary goals of Aim 1 were completed in Project Years 3 (see project schedule in Table 1), with the development of a carbon nanotube (CNT) liquid crystal elastomer (LCE) composite. The CNTs absorb light and convert it to heat, actuating the LCE. With this material, together with the heat-responsive liquid crystal elastomers (LCEs), magnetoactive composites, silicones, and hydrogels developed in previous years, embodied logic can be constructed that autonomously actuates in response to light, heat, magnetic fields, non-polar solvents, and water. The timing and shape changes associated with actuation can be controlled via the build sequence used during 3D printing.
(Aim 2, Multistable mechanisms.) We have experimentally, numerically, and analytically characterized the static and dynamic behavior of several multistable mechanisms, including motifs based on snapping beams and rotating polygons.
(Aim 3, System integration and theoretical framework.) In Aim 3, we integrated the materials and mechanisms from Aims 1 & 2 to explore autonomous soft robots with the ability to “compute” their trajectory based on distributed transduction events in the robot body (published in Science Advances in Year 4). We also published a conceptual framework for mechanical computing in the journal Nature.

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BIFURCATION-BASED ACTUATION FOR AUTONOMOUS SMART STRUCTURES

Award Number FA9550-19-1-0285

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Final Performance Report
Period 6/1/2019-5/31/2023

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PROJECT GOALS AND APPROACH

Nature provides many startling examples of plants that autonomously transform shape and function in response to environmental stimuli or sequences of stimuli. These natural adaptive systems achieve their responsiveness via combinatorial and sequential control logic that is embodied in the compositional (material) and structural (geometric) features of which they are composed. That is, the material-structure combination is itself the sensor, actuator, and local energy source, with embodied control determining when and how actuation should occur in response to environmental stimuli. This stands in stark contrast with the mechatronic systems that engineers typically use to attain comparable behaviors (e.g., electronic sensors, actuators, microprocessors, and tethered energy sources).

The ultimate *objective* of this project is to "embody" logic and sequencing of actuation events within a system's composition and geometry. Rather than using mechatronic systems composed of electronic sensors, actuators, batteries, and control systems, the material-structure combination itself will embody these functions. Attaining this objective will require new materials, a new theoretical framework, and new practical design tools that allow system design in the context of multiple stimuli-responsive materials and geometric nonlinearities. In this project we aim to address these fundamental and practical needs using both experimental and theoretical approaches.

Table 1. Proposed schedule by Aim and Task

	Year 1				**Year 2**				**Year 3**				**Year 4**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Aim 1: Responsive materials	X	X	X	X	X	X	X	X	X	X						
Stimuli-responsive materials	X	X	X	X	X	X	X	X								
Core-shell printing	X	X	X	X	X	X										
Material robustness / characterization			X	X	X	X	X	X	X	X						
Aim 2: Mechanism design			X	X	X	X	X	X	X	X	X	X	X	X		
New bistable mechanisms			X	X	X	X	X	X	X	X	X					
Modeling anisotropy / time-dependence			X	X	X	X	X	X	X	X	X	X	X	X		
Aim 3: System framework						X	X	X	X	X	X	X	X	X	X	X
Framework for multiple actuating units						X	X	X	X	X	X	X	X			
Multi-stimuli embodied logic						X	X	X	X	X	X	X	X	X	X	X

The basic approach of this project is to combine *stimuli-responsive materials* with *geometric nonlinearities*. The *materials* define which environmental stimuli the system can respond to (e.g., hydrogels swell in the presence of water). The *geometric nonlinearities*, on the other hand, define sets of stable and unstable morphologies. By carefully designing how and when these instabilities occur, small changes to the materials (e.g., a small amount of swelling) can trigger rapid, large-amplitude actuation (**Fig.1**A-C).[1] More formally, environmentally-triggered *self-actuation* can be designed to occur by choosing geometric parameters that lie near nonlinear bifurcation points. We will fabricate these systems using direct write 3D printing, which is selected because of its broad materials palette (the large number of compatible materials allows the system to respond to a large number of environmental stimuli). We will print our structures using materials designed to swell anisotropically when exposed to suitable stimuli (as defined by the material). Anisotropic swelling alters key geometric control parameters, which, if brought through specific bifurcation points, produce rapid, large- amplitude self-actuation events (Fig.1C), and, unlike most prior work, can do so *at specific times*, enabling sequencing. Moreover, the use of multiple active materials allows actuation decisions to be made based on *logical combinations of distinct environmental stimuli*. We use this bioinspired control strategy as a means to "embody" logic that defines how a structure changes shape and function in response to multiple environmental cues (Fig. 1D), without electronics, external control systems, or tethering.

To achieve the above, in this project the technical tasks are organized in the form of three *Specific Aims*:

[1] Y. Jiang, L. M. Korpas, J. R. Raney, "Bifurcation-based embodied logic and autonomous actuation," Nature Communications 2019;*10*:128.

1. Produce 3D printing "inks" and determine processing steps for printing structures from a collection of anisotropic stimuli-responsive materials;
2. Design bistable mechanisms and characterize how key geometric parameters determine the nonlinear response;
3. Create a system-level design and modeling framework and demonstrate systems of multi-stimuli-responsive embodied logic.

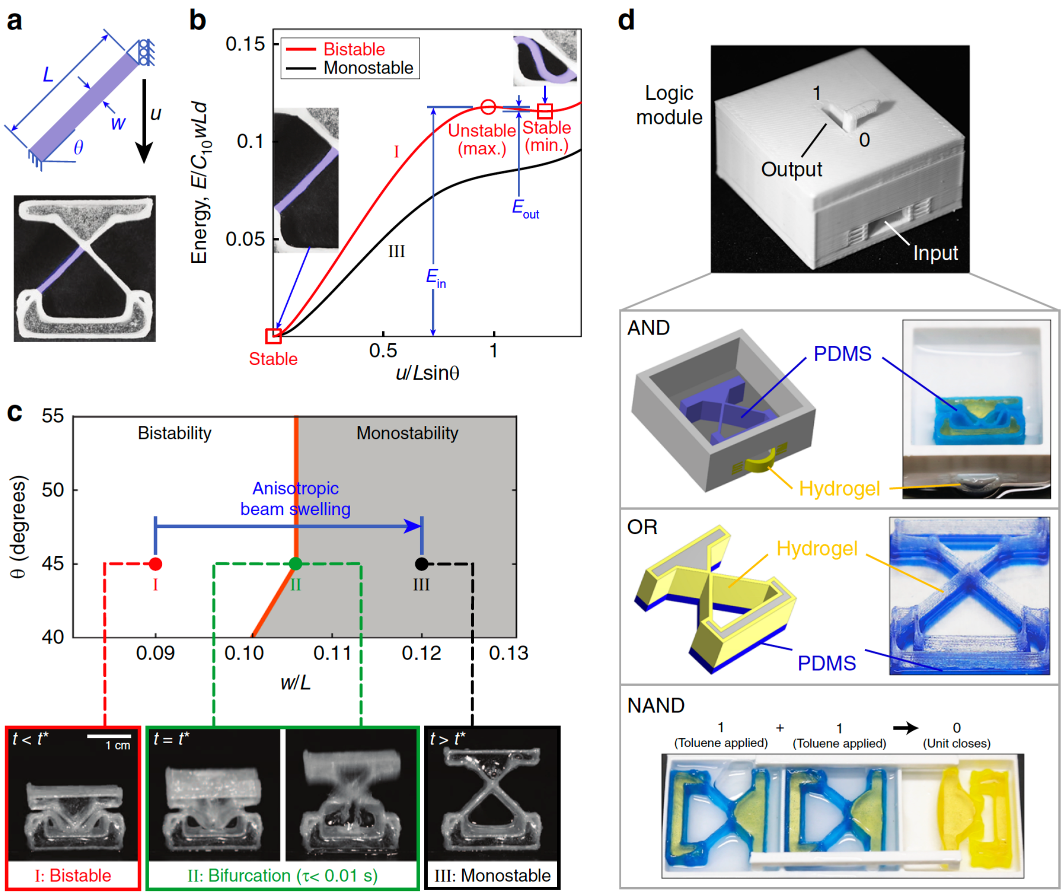


Figure 1. (a) Beams with key geometric parameters and boundary conditions. (b) Normalized strain energy, $E/(C_{10}wLd)$, where C_{10} is a material parameter in the Holzapfel-Gasser-Ogden (HGO)[2] material model and d is the out-of-plane thickness. (c) Geometric phase diagram mapping geometric parameters to mechanical behavior, with schematic overlay indicating the transition from bistable to monostable. (d) A logic module, which can act as one of several types of logic gates depending on the internal features.

ACCOMPLISHMENTS IN YEAR 4

The accomplishments of prior project years are described in detail in the previous annual reports. Here, we focus on the accomplishments finalized in Year 4, the concluding year of the project.

[2] G. A. Holzapfel, T. C. Gasser, R. W. Ogden, "A new constitutive framework for arterial wall mechanics and a comparative study of material models," Journal of Elasticity and the Physical Science of Solids 2000;*61*:1-48.

Accomplishments toward Specific Aim 1: 3D printable stimuli-responsive materials. As described in the project timeline (Table 1), the primary goals of Aim 1, namely, the development of 3D-printable stimuli-responsive materials for use as sensors/actuators in autonomous structures, was already completed prior to Year 4. However, we observed several interesting characteristics related to the *failure* of some of these materials. We therefore performed a few additional small studies involving characterization of microstructural evolution during mechanical failure of short-fiber soft composites, including studies that have now been published in *PNAS*, *Soft Matter*, and *Journal of Composite Materials*.[3]

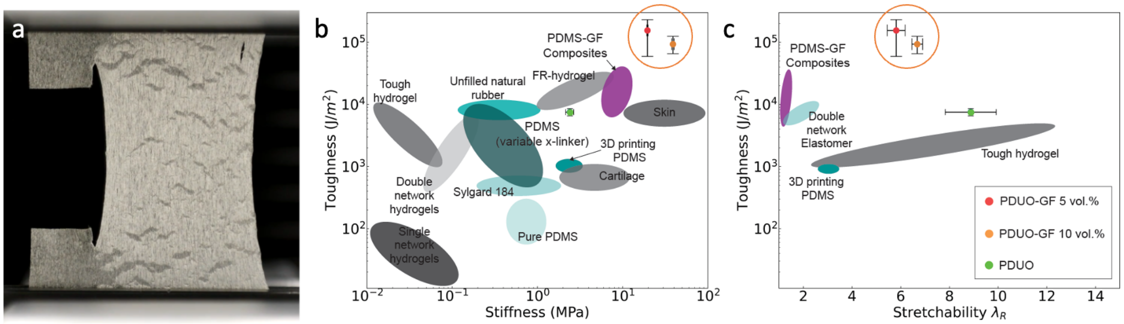


Figure 2. (a) An optical image of a notched composite being strained; even when subjected to very large strains, the silicone composite resists failure; (b-c) toughness vs. stiffness and toughness vs. stretchability, respectively, comparing the properties of our optimized silicone composites (circled in orange) to a variety of natural and synthetic materials. These composites have a stiffness comparable to skin yet have an order of magnitude higher toughness.

By manipulating the fiber orientation during the 3D printing process, improving the chemistry of the silicone matrix, and enhancing the strength of the fiber-matrix bond, these studies demonstrated that stimuli-responsive silicone composites can be made with orders of magnitude improved toughness, as well as improved stretchability (**Fig. 2**). Fig. 2a shows an optical image of the finalized glass fiber-PDMS composite. In this case, a notch has been cut in the specimen, and a stretch of approximately three has been applied using a commercial materials test system (Instron). The notch is not able to grow into the specimen despite this large stretch. Fig. 2b-c show toughness vs. stiffness and toughness vs. stretchability, respectively, for this composite, and compare its performance to other common natural and synthetic materials. In Fig. 2b, it is noteworthy that the stiffness of this composite is comparable to that of skin, but the toughness is an order of magnitude larger. Fig. 2c shows that this composite maintains a stretchability significantly larger than more conventional PDMS and PDMS composites.

[3] C. Mo, H. Long, J. R. Raney, Proceedings of the National Academy of Sciences 2022;119(28):e2123497119. C. Mo, R. Yin, J. R. Raney, Soft Matter 2022;18:7341-7347. C. Mo, R. Yin, H. Long, J. R. Raney, Journal of Composite Materials 2023;57(4):521-530.

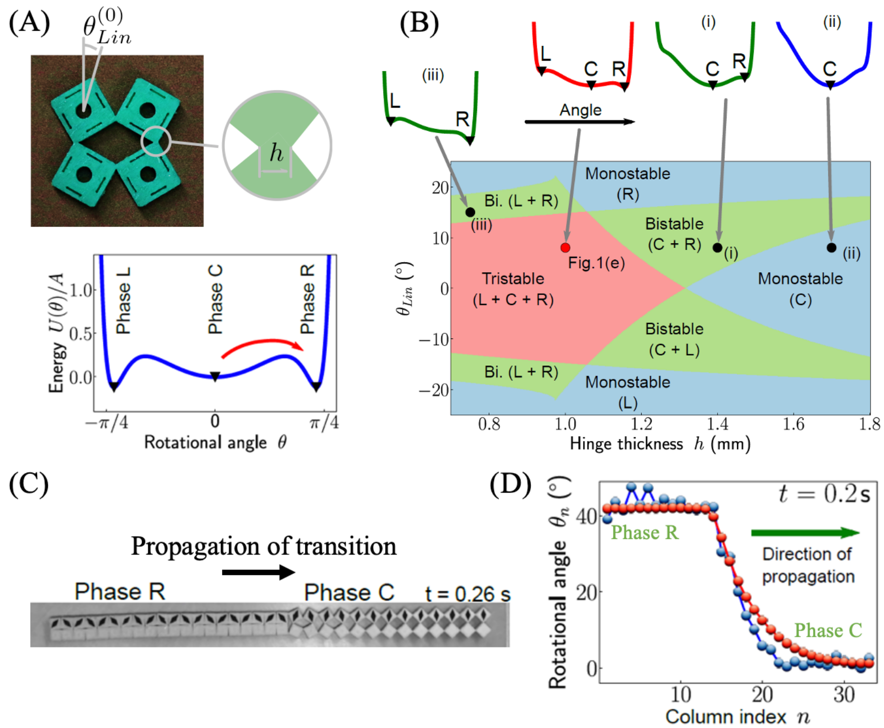


Figure 3. (A) A 2D tristable mechanism constructed with a simple hinged, rotating squares geometry; tristability is achieved via addition of permanent magnets in the adjacent faces of the squares; the three energy minima are analogous to distinct "phases" in materials; (B) The number and depth of the energy wells can be controlled via the hinge stiffness (determined by hinge thickness, h) and the angle used for initial fabrication; (C-D) If one unit is forced to change phase its associated conformation change will affect its neighbors, potentially producing a "transition wave" (topological soliton) that propagates through the structure affecting the spatial distribution of phases.

Accomplishments toward Specific Aim 2: Multistable mechanisms. In **Project Years 1-3** we focused primarily on designing, building, and modeling 2D multistable kirigami mechanisms based on rotating squares. We built a discrete model to allow numerical prediction of both static and dynamic behaviors of the system (**Fig. 3-4**) and integrated responsive materials which enable the systems to spontaneously respond to their environment.

The 2D mechanism is based on the classic rotating squares mechanism that has been previously studied for its interesting static properties, such as its negative Poisson's ratio.[4] We added permanent magnets to the adjacent faces of the squares to achieve multistability (Fig. 3A).[5] Up to three energy minima can be obtained, corresponding to the open state (faces of squares not in contact) and the two collapsed states (faces in contact, with rotational direction either clockwise

[4] J. N. Grima, K. E. Evans, "Auxetic behavior from rotating squares," Journal of Materials Science Letters 2000;*19*:1563.
[5] H. Yasuda, L. M. Korpas, J. R. Raney, "Transition waves and formation of domain walls in multistable mechanical metamaterials," Physical Review Applied 2020;*13*:054067.

or counterclockwise with respect to the open configuration). These three states are analogous to different "phases" in materials science. We therefore label them, e.g., as Phase L, Phase C, and Phase R. The number of phases (energy minima) and the respective depths of these minima can be controlled simply by the hinge stiffness (determined by the hinge thickness, *h*) and the initial angle assigned during fabrication (Fig. 3B). For example, as *h* becomes very large, the hinges are too stiff for the magnets to bend to the point of face-face contact, producing a "monostable" rotating square mechanism that only supports the open state (Phase C). Intermediate values of *h* support tristability (Fig. 3B). Just as in (e.g., ferromagnetic) materials, a change in phase in one unit, e.g., via the application of a force, will affect neighboring units. This can produce rich nonlinear dynamic effects, such as the rapid propagation of a "transition wave" (or topological soliton) through the system, affecting the spatial distribution of phases (Fig. 3C-D). In this way, not only can the phase of each individual rotating square unit represent a different "bit value", but, potentially, these different values will interact with one another, and in some sense "compute". The bit values stored in the different rotating squares constitute information that can be manipulated by integrating this multistable mechanism with stimuli-responsive materials (more in Aim 3 below).

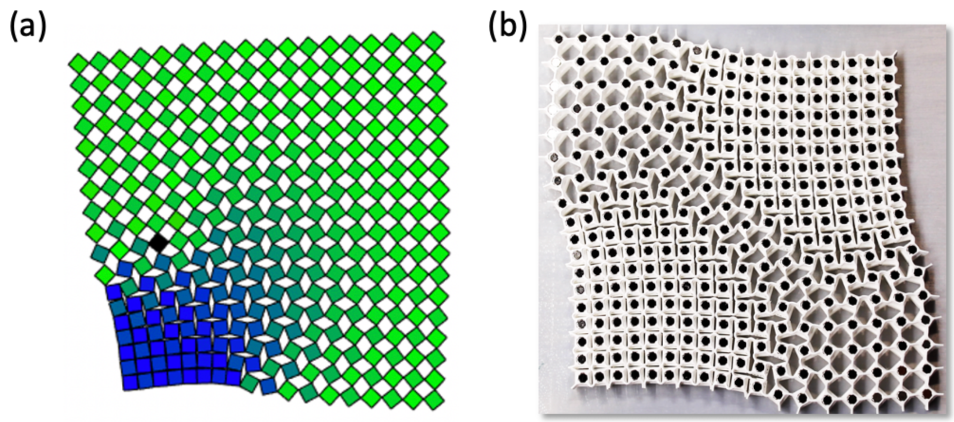


Figure 4. (a) A simulation of mechanical deformation of a 2D kirigami structure based on numerical analysis of the 2D equations of motion for the kirigami. (b) Experimental realization of a 2D rotating squares kirigami prototype. We used this prototype to quantify the fitting parameters of the model.

In **Project Year 3-4** we began to consider additional "chiral" mechanisms that produce 3D (out-of-plane) deformation as a result of in-plane rotations due to geometric frustration (**Fig. 5-6**). We are studying whether these effects can be harnessed in robots, specifically as a metamaterial that "computes" on its environmental inputs to alter the function of the robot (e.g., converting a walking robot into a swimming robot). Moreover, because different geometric states can be individually assigned locally (Fig. 6), the metamaterial supports a very large number of global states. Each of these may have different static (stiffness, Poisson's ratio, etc.) and dynamic (band gaps, soliton propagation, etc.) mechanical properties. Hence, these structures also have potential utility as reconfigurable mechanical systems.

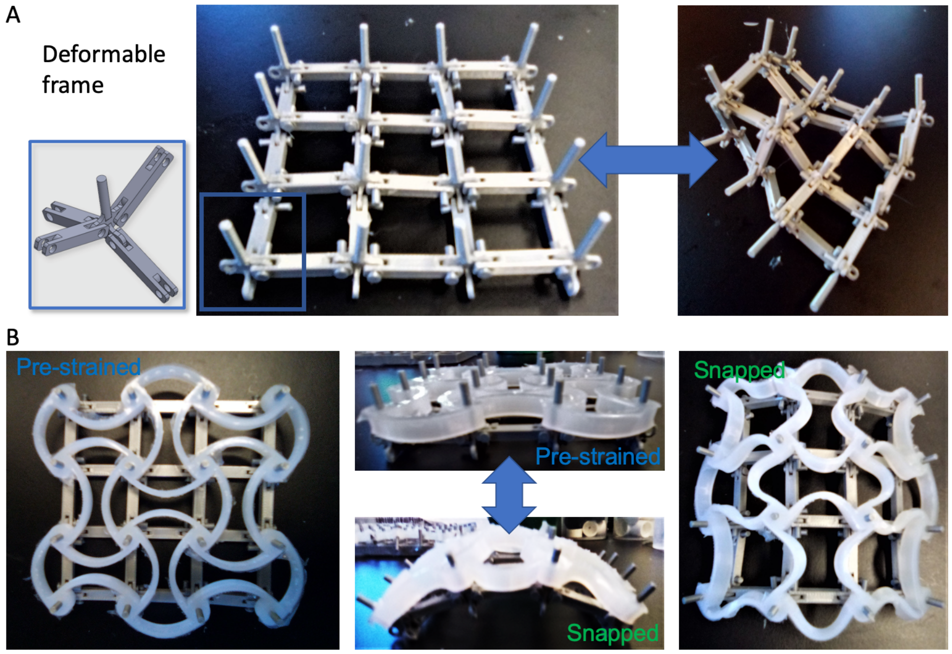


Figure 5. (a) The system includes a 3D-printed frame, which consists of rigid plastic units connected together. The hinges between the units are free to rotate. (b) When a silicone lattice is connected to the nodes of the frame, it becomes multistable. Internal rotations can cause frustration that forces out-of-plane motion.

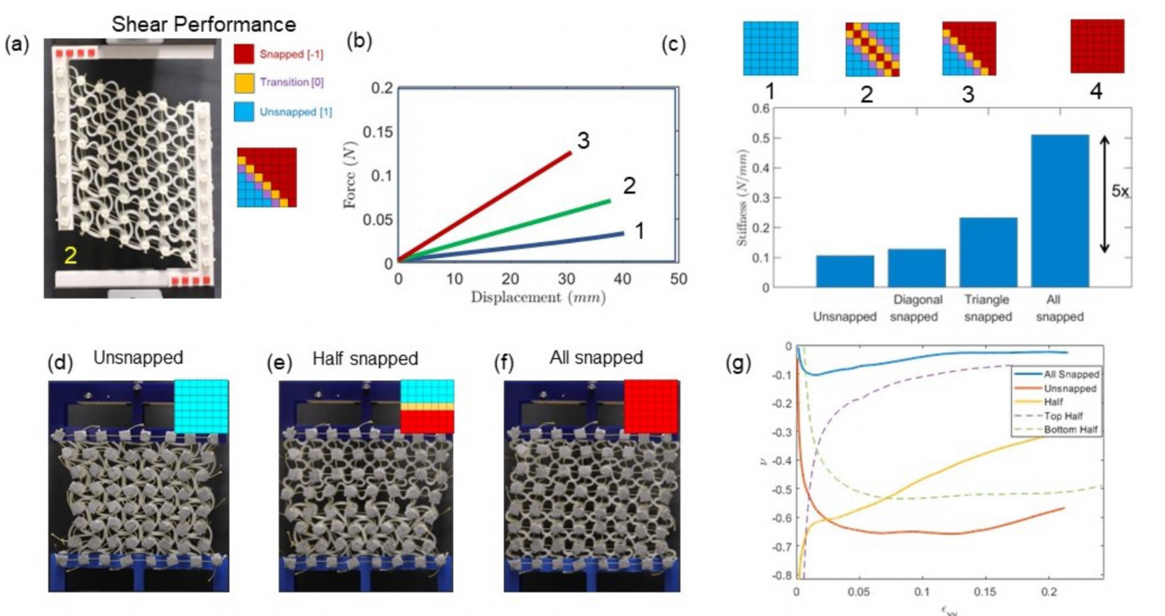


Figure 6. Because the chiral metamaterial is locally reconfigurable, many different global states can be assigned to the metamaterial. These different states often possess different mechanical properties, including static properties, such as stiffness and Poisson's ratio, but also dynamic properties, such as band gaps.

Accomplishments toward Specific Aim 3: Integration of multistability and active materials.

The idea of digital "embodied logic" as formulated in this project requires both multistability (i.e., Aim 2), which can be used to define the information state of the system, and stimuli-responsive materials (i.e., Aim 1), which enable the system to autonomously receive input from its environment. However, the integration of multiple active materials with nonlinear mechanical responses that are highly sensitive to the geometric parameters of the system is not trivial. The goal of Specific Aim 3 is to produce the theoretical framework and practical design tools necessary to enable this system integration.

In Project Year 4 we concluded this grant by demonstrating the utility of stimuli-responsive mechanical logic in the context of pneumatic robots. We explored two distinct strategies: (1) Incorporation of responsive materials in modular units that, when activated by the responsive material, manipulate the trajectory of the robot via mechanical constraints (**Fig. 7-12**); and (2) Use of responsive materials to directly regulate pneumatic logic in soft robots (**Fig. 13-14**). In both cases, the competition of several such events steers or changes the function of the robot according to a high-level set of commands, such as "walk across the room but avoid sources of heat above a certain temperature".

Our basic robot design is shown in **Figure 7**. The primary structure is the same "rotating-squares" kirigami mechanism that we have already studied extensively. A pneumatic actuator is placed between two kirigami layers. When air pressure is applied to the actuator it extends longitudinally, causing the kirigami to open. Small feet placed under the bottom kirigami layer allows this extension-contraction cycle to produce locomotion. The final component of the robot is a collection of modular defects which, like legos, can be easily added or removed at arbitrary locations in the robot.

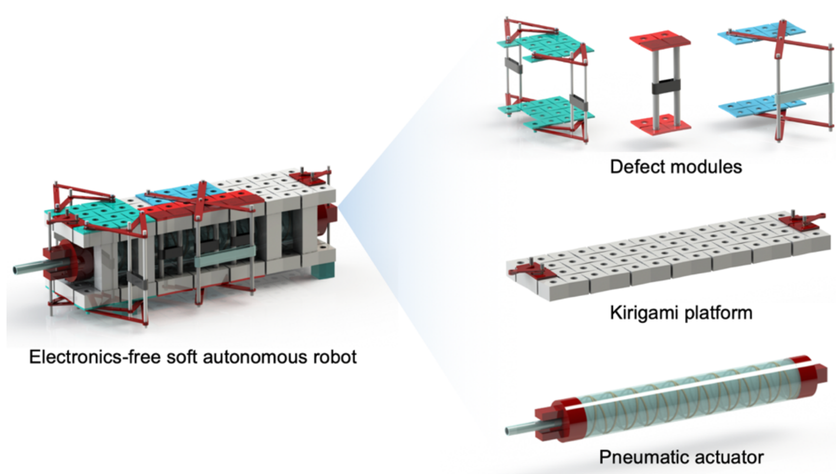


Figure 7. The kirigami soft robot consists of three primary layers: (1) a pneumatic actuator, which enables locomotion; (2) the kirigami, or "structural", layers, which provide mechanical support and act as attachment points for defects; and (3) defect modules (or "control modules"), which plug into the kirigami layers to manipulate their deformation, and, hence, the conformation and locomotion path of the robot.

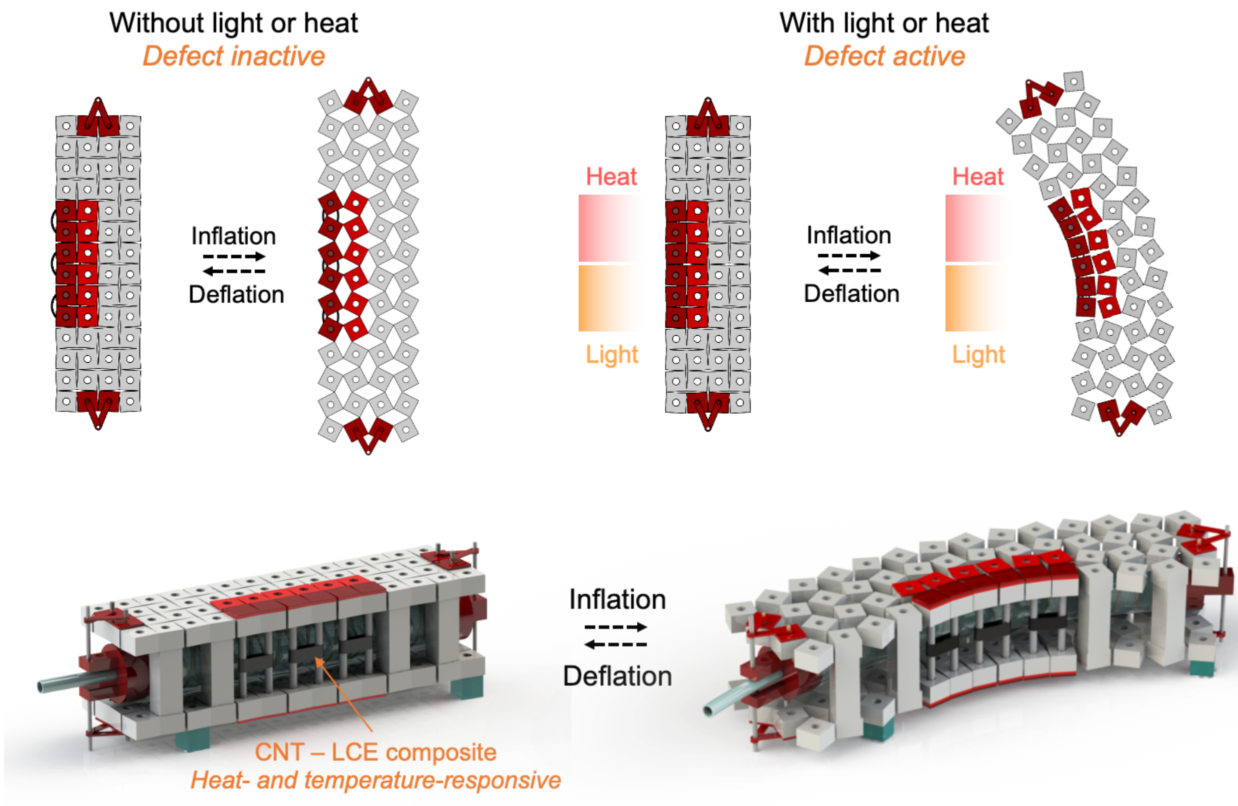


Figure 8. Because the kirigami is compliant, only small forces are required to affect the deformation of the structure. Defects, or "control modules (indicated by red squares), are activated or deactivated via interaction with the environment (heat or light, in this figure). These influences cause the kirigami to bend when it is inflated by the pneumatic actuator, causing the robot to turn.

Figure 8 shows the basic mechanism by which the modular defects can be activated by stimuli, and how this affects the shape (and, therefore, trajectory) of the robot. In this example, the modules are controlled by liquid crystal elastomers (LCEs) with embedded carbon nanotubes (CNTs). The LCEs contract when their temperature increases. Since CNTs can warm significantly as they absorb light, the CNTs enable the LCEs to also contract in response to light. In the example in Figure 8, the CNT-LCE composite is placed along one side of the robot. When light or heat impinge on this side of the robot, it curves in that direction, causing the robot to steer in the direction of the heat/light stimulus. Of course, the contraction of the CNT-LCE composite is a function of how much heat or light is impinging on it. In **Figure 9** we quantify this relationship by experimentally measuring the bending angle of the robot as a function of the distance *d* between the stimulus source and the robot and of the pressure in the pneumatic actuator. Figure 9(a) and Figure 9(b) show the bending angle of the robot when subjected to light and heat, respectively. The schematic in Figure 9(c) and the experimental images in Figure 9(d) show how this curvature change affects the robot trajectory. In this case, a modular defect was designed that bends the trajectory toward the stimulus (light). Similarly, Figure 9(e-f) show a schematic and experimental images demonstrating how defects can also be designed that bend the trajectory away from a stimulus (heat, in this case).

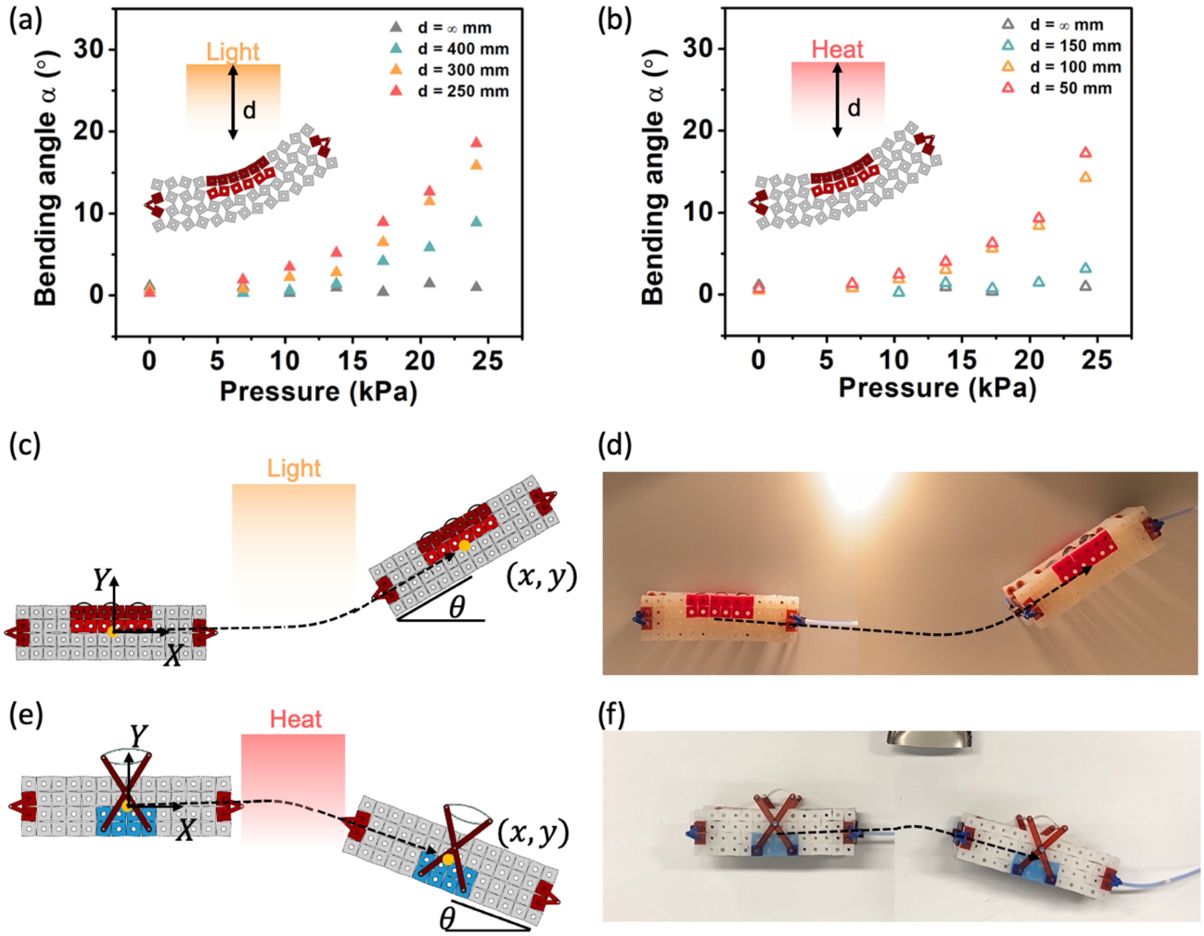


Figure 9. The amount of heat or light received by the defects of Figure 8 will determine to what degree the CNT-LCE composite contracts. (a) The effect of light exposure on the bending angle of the robot, as a function of the distance between light source and robot (*d*) and of the pressure in the pneumatic actuator; (b) the same data but now as a function of distance between heat source and robot (*d*); (c-d) a schematic and experimental images, respectively, showing how a defect can be designed that causes the trajectory of the robot to bend toward a stimulus (in this case, light); (e-f) a schematic and experimental images, respectively, showing how a defect can be designed that causes the trajectory of the robot to bend away from a stimulus (in this case, heat).

The experiments in Figure 9 demonstrate the feasibility of our basic idea, i.e., of *embodying the control system* in the robot itself, making use of modular control units to determine how the robot responds to its environment rather than any electronics. In fact, many other types of control modules can be envisioned beyond those demonstrated in Figure 9. We can also combine multiple control modules within the structure to produce competing effects. These defects could be designed to respond to the same or to different stimuli in the environment, depending on the desired functionality (e.g., the same defects shown in Figure 9 could be fabricated from hydrogels instead of LCEs, which would impart functionality in response to moisture changes rather than to heat/light). One of the key points to keep in mind is that *the control units are modular and easily added/removed*. Since they are responsible for determining the behavior of the robot, the distributed modules *constitute* the control system. There is no separate electronic control system. The user of the robot would determine the desired high-level behavior (e.g., "move toward light while avoiding moisture") and select the modules that would impart that functionality. The body of the robot would then compute an appropriate trajectory based on the distributed structure and modules within the robot itself. **Figure 10** provides an example of how we characterize the action of a control module and its effect on the bending angle of the robot. In this case, the robot head is autonomously directed toward heat or light, causing the robot to steer toward these stimuli.

Finally, we have begun to quantify the effect of multiple control modules. **Figure 11** shows one simple example of the complexities that can arise in this scenario. In this case, two control modules, which can be individually activated, are placed on opposite sides of the robot. If neither or both of these are active, the robot has zero curvature and moves directly forward when pneumatically actuated. If only one of the modules is active (e.g., heat is applied to one side of the robot only), the robot will have non-zero curvature (which can be either positive or negative, depending on which module is active). As shown in Figure 11, this allows us to construct a *truth table* that captures the *distributed logic* embodied in the robot/module structure. Such truth tables are used in discrete mathematics and logic to describe the outputs of logic operations (AND, OR, XOR, etc.) as a function of all possible inputs. Our truth tables are analogous to these, but quickly grow quite complex. For example, they can include a large number of inputs (a function of the number of modules and their spatial distribution). **Figure 12** shows the experimental characterization of a NOR gate. We have similar data for XOR, OR, and AND behaviors.

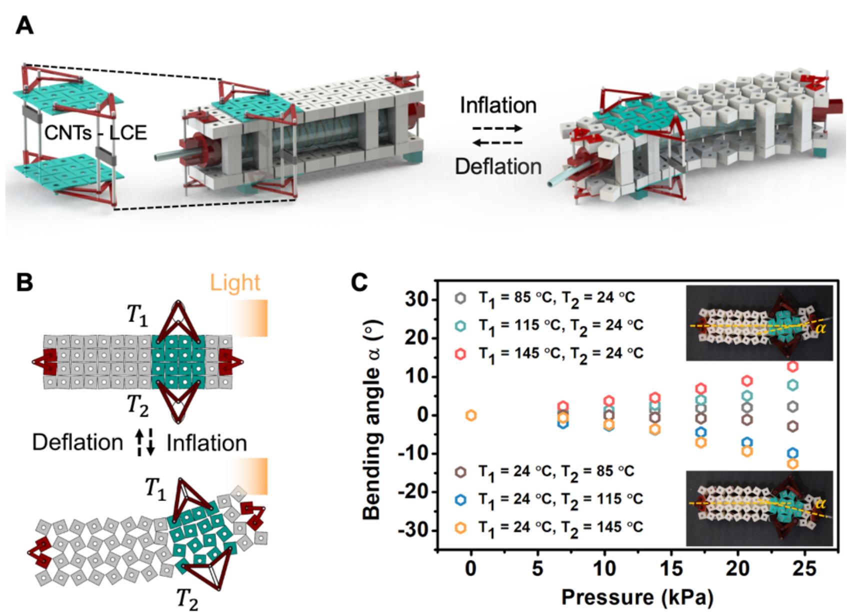
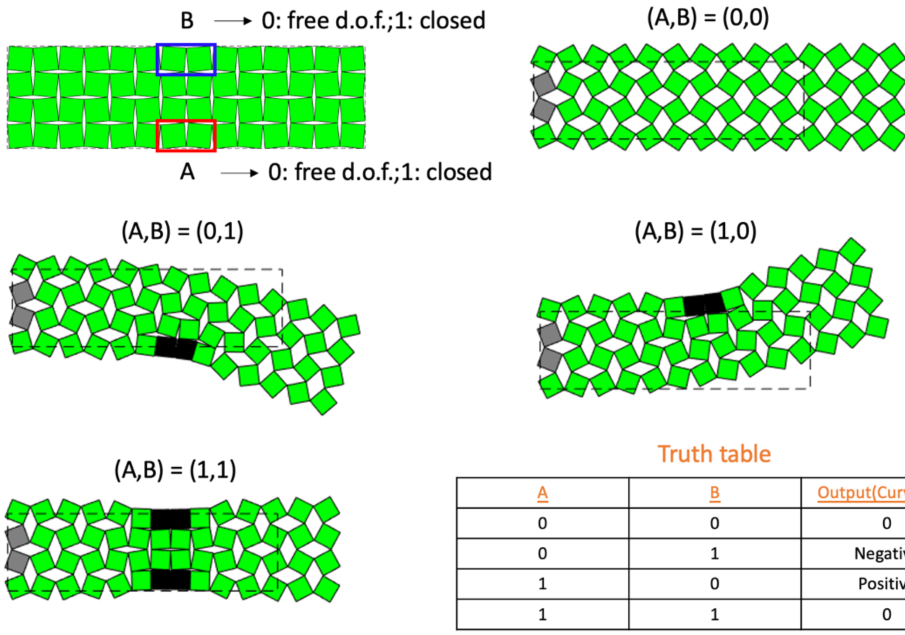


Figure 10. Experimental measurements of a control module designed to steer the robot toward a stimulus. Here we measure the temperatures T_1 and T_2 on the two sides of the module when it is subject to different amounts and locations of light. We relate this to the resulting bending angle of the robot.



A	B	Output(Curvature)
0	0	0
0	1	Negative
1	0	Positive
1	1	0

Figure 11. Combining multiple control modules can lead to distributed logic; the body of the robot will have different conformations depending upon the evaluation of multiple, distributed modules. In this example, two control modules, *A* and *B* can be independently activated on the two opposite sides of the kirigami robot. If neither is activated (A,B) = (0,0) or if both are activated (A,B) = (1,1), the robot curvature remains zero, and the trajectory of the robot proceeds directly forward. If only one of the modules is activated the robot will have non-zero curvature (either positive or negative, depending on which module is active).

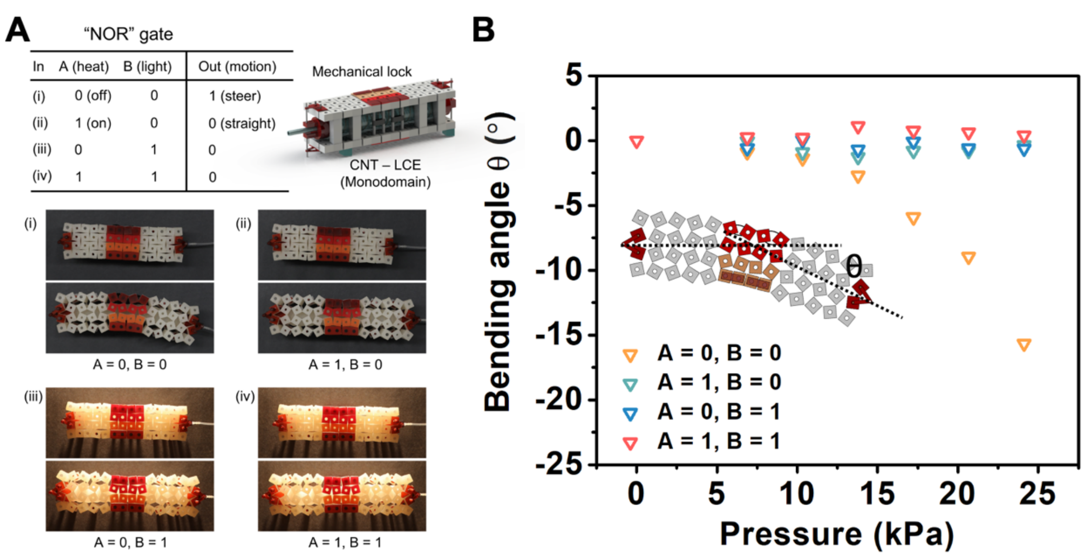


Figure 12. Two modules A and B can be used to realize a NOR behavior for the trajectory of the robot.

As mentioned, the second approach is to use the responsive materials to instead regulate pneumatic logic directly. For example, one could require that heat is present in a certain location to open or close a pneumatic valve (regulated by a liquid crystal elastomer). This could be used to enable pneumatic logic in response to heat in the environment, e.g., changing the shape, properties, or function of a robot. While this work is in an early stage, **Figures 13-14** show the feasibility of this approach. We will continue to investigate these ideas in future work.

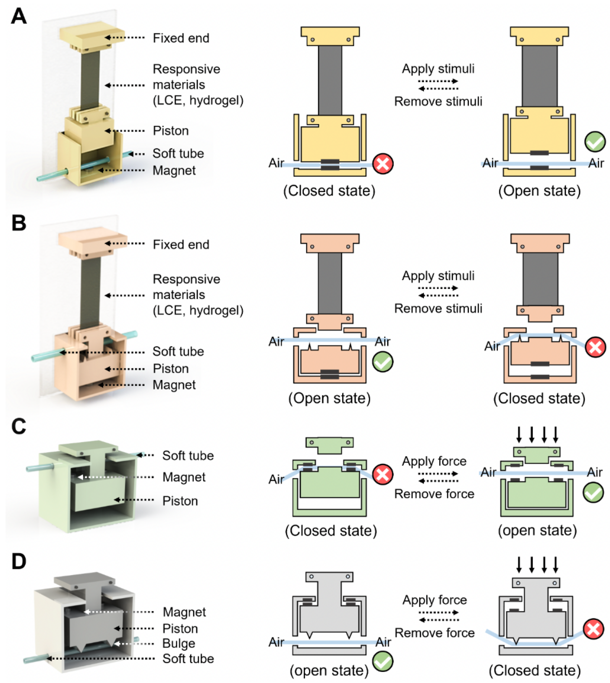


Figure 13. We designed modules that can turn pneumatic channels on or off when relevant stimuli are encountered.

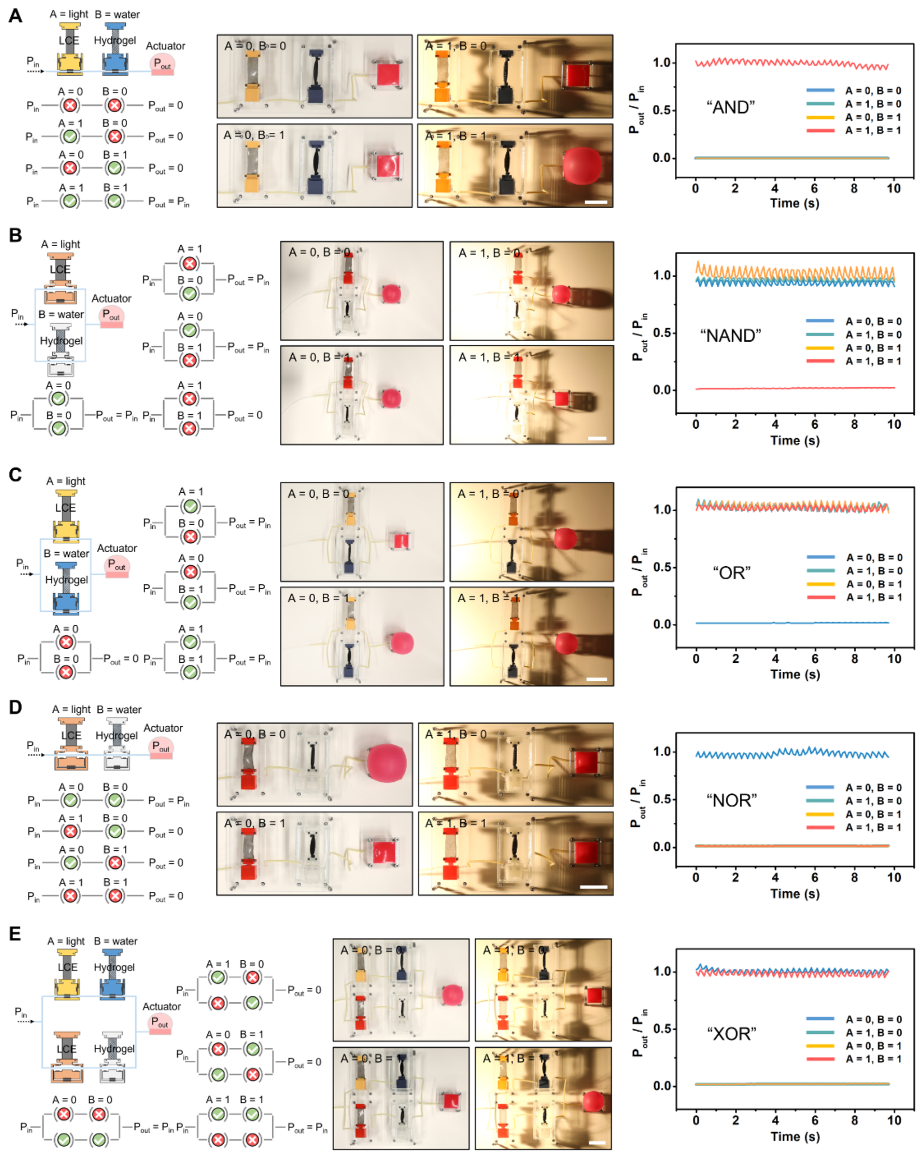


Figure 14. By combining multiple stimuli-responsive pneumatic valves, arbitrary combinational logic can be achieved.

TRAINING

Post-doc	Weijian Jiao	0.0 mo. (worked ~ 3 mo. But not funded by the grant)
Post-doc	ABM Tahidul Haque	0.0 mo. (worked ~ 6 mo. But not funded by the grant)
Post-doc	Qiguang He	0.0 mo. (worked ~ 9 mo. But not funded by the grant)
PhD student	Rui Yin	12.0 mo.
PhD student	Yucong Hua	0.0 mo. (worked ~ 6 mo. But not funded by the grant)

DISSEMINATION

Outcomes of this project were disseminated through journal publications and invited seminars.

Journal publications (including manuscripts currently in review):

Project Year 4:

1. W. Jiao, H. Shu, H. Yasuda, V. Tournat, J. R. Raney†, "Phase transitions in 2D multistable mechanical metamaterials via collisions of soliton-like pulses," Nature Communications (*in review*).
2. H. Yasuda, H. Shu, W. Jiao, V. Tournat, J. R. Raney, "Nucleation of transition waves via collisions of elastic vector solitons," Applied Physics Letters 2023;123(5):051701.
3. Q. He, R. Yin, Y. Hua, W. Jiao, C. Mo, H. Shu, J. R. Raney, "A modular strategy for distributed, embodied control of electronics-free soft robots," Science Advances 2023;*9*(27):eade9247.
4. C. Mo, P. Perdikaris, J. R. Raney, "Accelerated design of architected solids with multi-fidelity Bayesian optimization," Journal of Engineering Mechanics 2023;*149*(6): 04023032.
5. C. Mo, R. Yin, H. Long, J. R. Raney, "Effect of the Fiber-Matrix Bond on the Failure Characteristics of Glass Fiber-Polydimethylsiloxane Composites," Journal of Composite Materials 2023;57(4):521-530.
6. Y. Wang, R. Yin, L. Jin, M. Liu, Y. Gao, J. R. Raney, S. Yang, "3D printed photoresponsive liquid crystal elastomer composites for free-form actuation," Advanced Functional Materials 2023;*33*(4):2210614.
7. C. Mo, R. Yin, J. R. Raney, "Direct ink writing of tough, stretchable silicone composites," Soft Matter 2022;*18*:7341-7347.
8. H. Yasuda, K. Johnson, V. Arroyos, K. Yamaguchi, J. R. Raney, J. Yang, "Leaf-like origami with bistability for self-adaptive grasping motion," Soft Robotics 2022;9(5):938-947.
9. C. Mo, H. Long, J. R. Raney, "Tough, aorta-inspired soft composites," Proceedings of the National Academy of Sciences 2022;*119*(28):e2123497119.

Journal publications from previous project years:

10. Y. Miyazawa, H. Yasuda, H. Kim, J. H. Lynch, K. Tsujikawa, T. Kunimine, J. R. Raney, J. Yang, "Heterogeneous origami architected materials with variable stiffness," Communications Materials 2021;2:110.
11. H. Yasuda, P. R. Buskohl, A. Gillman, T. D. Murphey, S. Stepney, R. A. Vaia, J. R. Raney, "Mechanical computing," Nature 2021;598:39-48.
12. L. M. Korpas, R. Yin, H. Yasuda, J. R. Raney, "Temperature-responsive multistable metamaterials," ACS Applied Materials & Interfaces 2021;13(26):31163-31170.

13. H. Yasuda, K. Yamaguchi, Y. Miyazawa, R. Wiebe, J. R. Raney, J. Yang, "Data-driven prediction and analysis of chaotic origami dynamics," Communications Physics 2020;3:168.
14. H. Yasuda, L. M. Korpas, J. R. Raney, "Transition waves and formation of domain walls in multistable mechanical metamaterials," Physical Review Applied 2020;13:054067.

Conferences and academic seminars, including:

Project Year 4:

- A.B.M.T. Haque, S. Ferracin, and J.R. Raney, Symposium on Mechanical Metamaterials, ASME IMECE, Columbus, OH, November 2022.
- W. Jiao, Q. He, H. Shu, and J.R. Raney, Symposium on Mechanical Metamaterials, ASME IMECE, Columbus, OH, November 2022.
- W. Jiao, Q. He, H. Shu, and J.R. Raney, Symposium on Controlling Mechanical Waves with Metamaterials, Society of Engineering Science annual meeting, College Station, TX, October 2022.
- H. Shu, H. Yasuda, W. Jiao, V. Tournat, and J.R. Raney, Symposium on Controlling Mechanical Waves with Metamaterials, Society of Engineering Science annual meeting, College Station, TX, October 2022.
- Invited talk, Symposium on Transforming (Meta-)Materials and (Meta-)Structures, SIAM annual meeting, Pittsburgh, PA, July 2022.
- Invited talk, International Symposium on Nonlinear Acoustics, Oxford, UK, July 2022.
- Invited talk, Symposium on Architected Materials, US National Congress on Theoretical and Applied Mechanics, Austin, TX, June 2022.

Conferences and academic seminars from previous project years:

- Invited talk, Symposium on Nonlinear Acoustic Metamaterials and Phononics, 182nd meeting of the Acoustical Society of America (ASA), Denver, CO, May 2022.
- Invited talk, Symposium SB03 – Robotic Materials for Advanced Machine Intelligence, Materials Research Society spring meeting, Honolulu, HI, May 2022.
- Invited talk, General Motors Global Research & Development, August 2021 - *virtual due to COVID-19*
- Invited talk, "Information processing in kirigami-inspired mechanical systems" Virtual Research Seminar Series on Complex Active and Adaptive Material Systems, July 2021 *virtual due to COVID-19*
- J.R. Raney, invited talk, ASCE EMI Architected Materials Workshop, April 2021 – *virtual due to COVID-19*
- J.R. Raney, invited talk, Symposium on Design, Synthesis, and Characterization of Architected Materials for Structural Applications, MRS Spring Meeting, April 2021 – *virtual due to COVID-19*

- J.R. Raney, keynote talk, DARPA Nature as Computer Workshop, March 2021 – *virtual due to COVID-19*.
- J.R. Raney, invited talk, 3M Tech Forum, November 2020 – *virtual due to COVID-19*.
- J.R. Raney, Gordon Research Conference on Multifunctional Materials and Structures, Ventura, CA, January 2020.
- L.M. Korpas, H. Yasuda, J.R. Raney, ASME IMECE, Salt Lake City, UT, November 2019.
- J.R. Raney, SES annual meeting, St. Louis, MO, October 2019.

HONORS

- J.R. Raney, NSF CAREER Award (2023)
- J.R. Raney, Invited to Editorial Board, *Programmable Materials*, Cambridge University Press (2022)
- J.R. Raney, Invited to Editorial Board, *Communications Engineering*, Springer/Nature (2021)
- J.R. Raney, DARPA Young Faculty Award (2020)

TECH TRANSFER

"*Control method for compliant robots*," Q. He, R. Yin, Y. Hua, W. Jiao, C. Mo, H. Shu, J. R. Raney, full patent filed (2/23/2023), associated with US Provisional No.: 63/313,013 (filed 2/23/2022).

"*Expansile devices for treatment of organ prolapse and other applications*," J. R. Raney, C. X. Hong, M. Cioban, H. Yasuda, C. Mo, Penn Filing Number 20-9199, PCT filed (11/6/2020), PCT/US2020/059283.

PARTICIPANTS (funded)

Jordan R. Raney (PI): 1.0 mo.

Rui Yin (PhD student): 12.0 mo.

Total Participants: In Year 4, **1 PhD student** received funding from the project. If one also includes those who have not received funding directly from this project but who contributed to it in various ways (and benefited from it by associated training), then the numbers become: **3 postdocs**, **2 PhD students**, and **1 Master's students**.

PRODUCTS

Journal articles:

1. W. Jiao, H. Shu, H. Yasuda, V. Tournat, J. R. Raney†, “Phase transitions in 2D multistable mechanical metamaterials via collisions of soliton-like pulses,” Nature Communications (*in review*).
2. H. Yasuda, H. Shu, W. Jiao, V. Tournat, J. R. Raney, “Nucleation of transition waves via collisions of elastic vector solitons,” Applied Physics Letters 2023;123(5):051701.
3. Q. He, R. Yin, Y. Hua, W. Jiao, C. Mo, H. Shu, J. R. Raney, “A modular strategy for distributed, embodied control of electronics-free soft robots,” Science Advances 2023;*9*(27):eade9247.
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7. C. Mo, R. Yin, J. R. Raney, “Direct ink writing of tough, stretchable silicone composites,” Soft Matter 2022;*18*:7341-7347.
8. H. Yasuda, K. Johnson, V. Arroyos, K. Yamaguchi, J. R. Raney, J. Yang, “Leaf-like origami with bistability for self-adaptive grasping motion,” Soft Robotics 2022;9(5):938-947.
9. C. Mo, H. Long, J. R. Raney, “Tough, aorta-inspired soft composites,” Proceedings of the National Academy of Sciences 2022;*119*(28):e2123497119.
10. Y. Miyazawa, H. Yasuda, H. Kim, J. H. Lynch, K. Tsujikawa, T. Kunimine, J. R. Raney, J. Yang, “Heterogeneous origami architected materials with variable stiffness,” Communications Materials 2021;2:110.
11. H. Yasuda, P. R. Buskohl, A. Gillman, T. D. Murphey, S. Stepney, R. A. Vaia, J. R. Raney, “Mechanical computing,” Nature 2021;598:39-48.
12. L. M. Korpas, R. Yin, H. Yasuda, J. R. Raney, “Temperature-responsive multistable metamaterials,” ACS Applied Materials & Interfaces 2021;13(26):31163-31170.
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14. H. Yasuda, L. M. Korpas, J. R. Raney, “Transition waves and formation of domain walls in multistable mechanical metamaterials,” Physical Review Applied 2020;13:054067.

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5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5e. TASK NUMBER

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this project was to develop the concept of “embodied logic” and to enable sequenced autonomous actuation that is determined solely by a system’s composition and geometry. Rather than using mechatronic systems composed of electronic sensors, actuators, batteries, and control systems to achieve autonomous action (as is typical in robotics) the material-structure combination itself may embody these functions, similar to natural systems like the Venus flytrap.

15. SUBJECT TERMS
Embodied logic, autonomous materials, nonlinear mechanisms, stimuli-responsive materials

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** / **19b. TELEPHONE NUMBER** *(Include area code)*
unclassified	unclassified	unclassified		23	Jordan R. Raney / (215) –573-9928

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