Annual Performance Report

This document presents the progress of the research grant **Fast morphing multi-stable structures made from shape-programmable bio-inspired composites**, with agreement number **FA9550-16-1-0007**, for the period of performance October 2015 to October 2016.

1. Objectives

The objectives of our research remain unchanged from those presented in the original proposal: This project aims to exploit the exciting possibilities for large shape reconfiguration and inherent sensing offered by programmable matter structures to realise radical geometric adaptation for bio-inspired morphing systems.

2. Status of Effort

In the first year of this project, we studied: I) Synthetic snapping structures inspired by the Venus flytrap leaf, and II) Biological, multistable mechanism underlying snapping of the earwig wing. In part (I) we use a magnetic alignment technology to produce microstructured composites that are able to snap following the design principles found in the leaves of the Venus flytrap. The resulting artificial structures combine the fast response times of the natural leaf with the high stresses generated by continuous fiber composites, with the advantage of offering a lot of freedom in terms of reinforcement design. In part (II) we study the design principles of another biological structure that undergoes snapping: the wings of the earwig. To this end, the purely passive shape adaptation mechanism of buckling-induced twisting of wings was first introduced. The load types and cases acting on the component designed to buckle were investigated. For a wing spar as the component to undergo instability, the dominant loading is shear resulting in the development of a diagonal tension field in the postbuckling regime. To tailor the onset of buckling for a composite spar, an analytical model for the buckling of anisotropic plates loaded in shear has been derived. More details about these projects are presented below.

3. Accomplishments/New findings

Programmable material systems capable of self-shaping enable novel functionalities in several application fields. Shape adaptation is prevalently achieved exploiting diffusion-driven swelling or nano-scale phase transitions. Utilization of these effects significantly limits real implementation due to the slow response, environmental dependence and material-specific phenomena. We have begun to address these shortcomings by generating snapping, programmable shells resulting from the hierarchical material design exhibited by the Venus flytrap leaf. Moreover, the design principles underlying the snapping motion of another biological structure, the wings of the earwig, started to be explored.

3.1. Research results

I. Synthetic snapping structures inspired by the Venus flytrap leaf [1]

Tailoring the micro-structure by magnetically-driven alignment of micrometric hard platelets (fig.1A-B) allows us to locally tune the pre-strain and stiffness anisotropy of the composite to produce fast and large shape adaptation exploiting structural multi-stability.

[1] Results presented at "17th European Conference on Composite Materials" (ECCM16) and MRS Fall Meeting 2016, and submitted in archival form in the paper ***Programmable snapping composites with bio-inspired architecture.*** Bioinspiration & Biomimetics, 2016. See the publication section for details.

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This approach enables the fabrication of complex shapes showing non-orthotropic curvatures and stiffness gradients, as illustrated by the curve (blue) lines in Fig. 1.A, radically extending the design space when compared to conventional fibre-reinforced composites. We demonstrate this by faithfully mimicking the radial-tangential pre-strain of the Dionaea Muscipula leaf (Venus fly trap) shown in Fig.1C-D, which facilitates the snapping action producing its rare hunting functionality.

The response of the obtained synthetic Venus leaf was experimentally studied by means of digital image correlation (DIC), as seen in the experimental setup in Fig.2A. The obtained stable shapes associated with the shell (right and left) and the unstable shape as the Leaf snaps-through are shown in Fig.2.B. A sequence of snap shots as a leaf undergoes snap-through is shown in Fig 2.C for illustrating

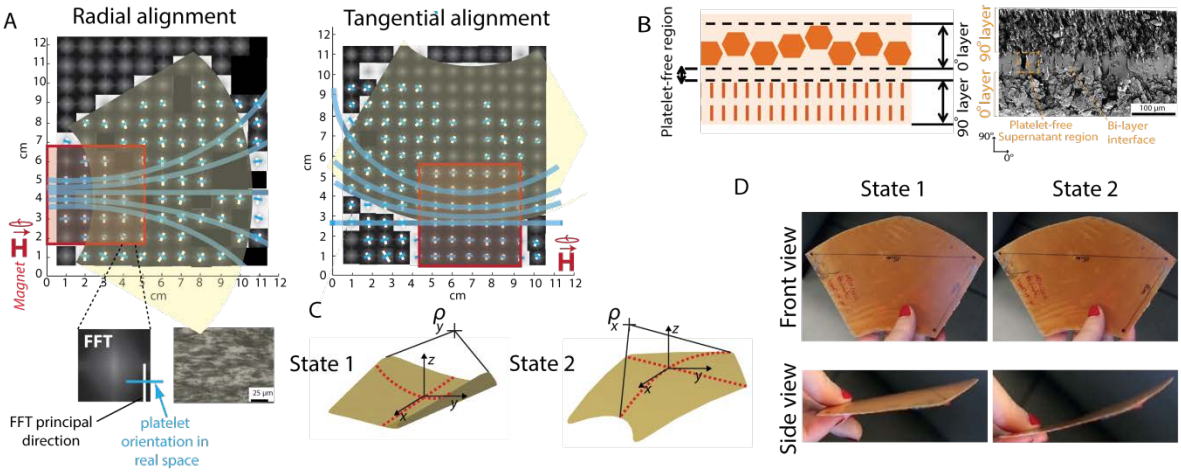

Fig. 1: Multistable plate mimicking the venus flytrap mechanism created by magnetic alignment

the large change in shape exhibited by the specimen. The displacement of a point in the leaf shown in Fig2.D illustrates the fast response and settling time of the shell, having a total time for changing between state 1 at 0 mm to state 2 at 4 mm of displacement in approximately 500 ms. However, it should be noted that the snapping shell has a very fast rise time of approximately 30 ms. It is evident that the structure is lightly damped and undergoes several cycles before settling, as a result a compromise between the damping of the system needs to be found for the rise and settling times to obtain the desired fast response to equilibrium.

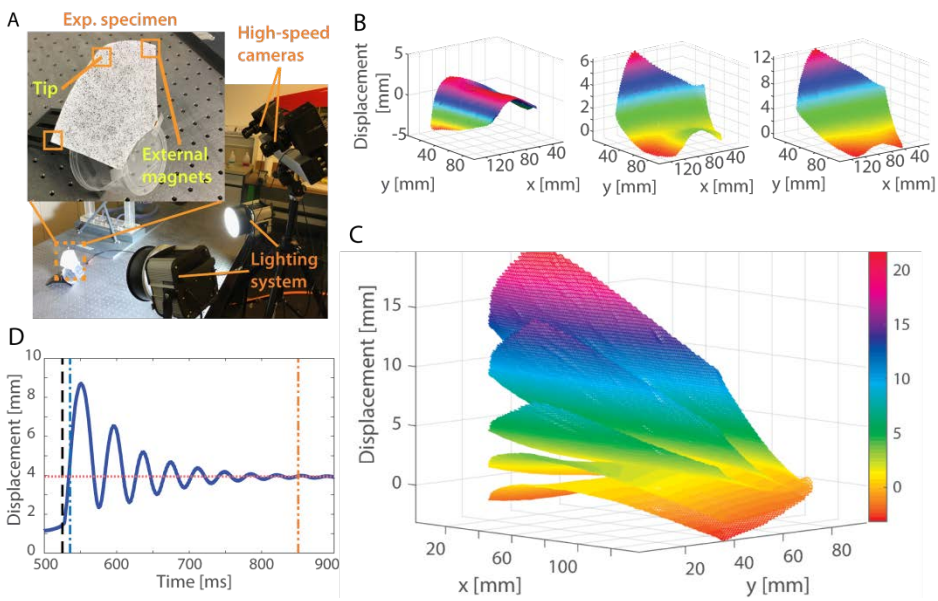

Fig. 2: Dynamic response of synthetic bioinspired Venus Flytrap leaf.

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II. Biological, multistable mechanism underlying snapping of the earwig wing

The earwig uses a sophisticated, spring-loaded bistability mechanism for folding and unfolding its wing. It thereby achieves the highest ratio of folded to unfolded wing area in the animal kingdom. We have started to numerically study this folding process of the wing. The folding pattern could be successfully reproduced and biology literature was reviewed. Our extended aim has been to utilize 3D printing techniques to create an artificial system mimicking the earwig's behaviour in order to study the intricacies of folding and bistability when extended. The findings are relevant directly towards the development of a novel deployment mechanism for wings, solar panels and similar, faceted devices, as well as indirectly towards multistable surfaces described in section III.

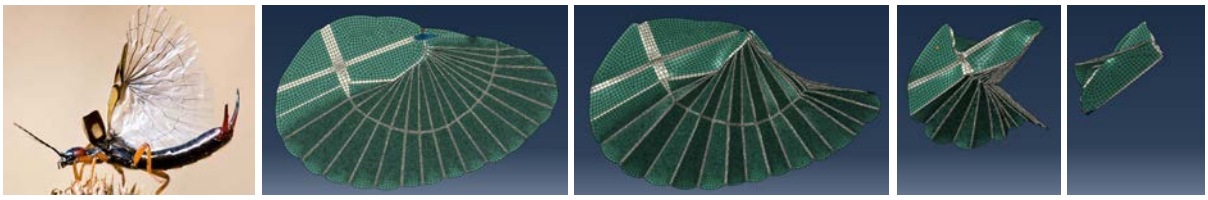

Fig. 3: Earwig wing example and numerically computed folding process

Two approaches to manufacturing are being studied at present, namely fused deposition modelling (FDM) and digital light processing (DLP) 3D printing to validate the modelling effort. The first follows a route to larger structures, produced by multimaterial fused deposition modelling. The approach allows us to modulate stiffness in the range 0.1MPa to 5-10 GPa while working with polymer or partially filled polymer systems. First experiments have delivered proof of concept samples of the earwig wing, which may be used to study extension-retraction as well as validate the modelling design approach. Our future efforts will focus on refining the manufacturing to yield actuating structures, and translate the designs into structural composite materials.

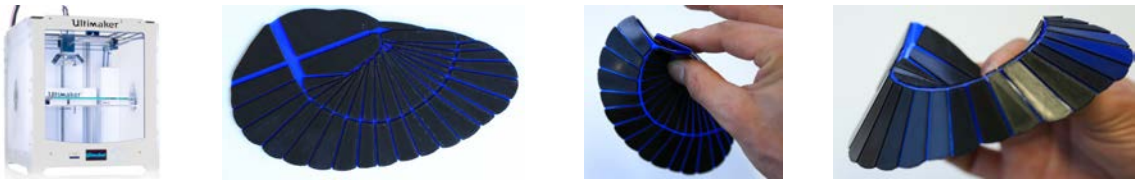

Fig. 4: First multimaterial prototypes produced by fused deposition modelling (FDM) may be folded as the biological example (wing length 150 mm).

To produce samples on similar length scales to the natural example, we have also been studying DLP 3D printing combined with soft material encapsulation. The high level of complexity combined with multimaterial design allows us to locally structure the wing for applications such as flying microrobotics.

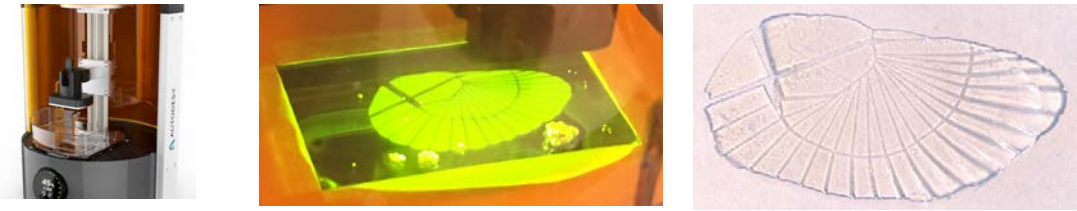

Fig. 5: DLP printed earwig wing on similar length scales to the biological example (wing length 30 mm).

III. Implementation of bio-inspired multistable mechanisms in morphing applications

Bistable shell elements, like the earwig's wing example, can be transferred into patterned structures made from many bistable elements. Our idea is to create mechanical "metamaterial" structures in which each of the bistable elements introduces a local change in the curvature of the global shell. This possibility of many individual, local curvature changes leads to multistable shells with many possible stable configurations. These configurations can be pre-programmed in a spatially distributed fashion by locally changing

- the bistable element geometry,
- the material stiffness distribution, or
- the material's internal orientation.

The actuation of individual or multiple elements can either be achieved actively by external stimuli, such as temperature, electric or magnetic fields, moisture or dedicated actuators, or passively by global strains or curvatures. Prediction algorithms for the global shape changes induced by local snapping events have been developed and are currently being evaluated. It has further been shown that bistable elements can be produced by commercially available 3D printing systems, leading to large freedom in the design of morphing surfaces.

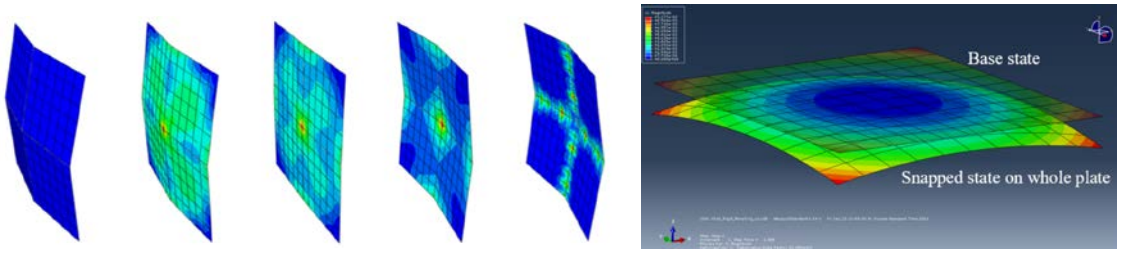

Fig. 6: a) Snap-through process and strains of single bistable element. b) prediction of global, multi-element shapes before/after snapping of constituting elements

4. Personnel Supported

I. Dr. Jakob Faber has been involved in the project from October 2016. He is currently focused on discovering novel structural topologies enabling the large reconfiguration of morphing systems drawing inspiration from biological examples.

II. Dr. Kunal Masania has been involved in the project since October 2015 and is focused on additive manufacturing and transfer of designs into structural composite materials.

5. Publications

5.1. Conference proceedings

I. A. F. Arrieta[2], J. Schmied, H. Le Ferrand, P. Ermanni, A. R. Studart. ***Magnetically Reinforced Multi-Stable Shells for Bio-Inspired Shape Adaptation.*** 17th European Conference on Composite Materials (ECCM), 26 – 30 July, Munich, Germany, 2016.

5.2. Journal papers

I. J. Schmied, H. Le Ferrand, P. Ermanni, A. R. Studart, A. F. Arrieta. ***Programmable snapping composites with bio-inspired architecture.*** Bioinspiration & Biomimetics, 2016. (accepted).

[2] Presenting author

5.3. Planned publications for next period

I. **Bioinspired topologies for bistable large reconfiguration, journal paper:** Investigation of the response and design possibilities offered by the bioinspired topologies for morphing found in Earwigs.

II. **Earwig study, journal paper:** Full investigation showing the simulation of the shape adaptation mechanisms enabling the enabling large shape adaptation on Earwigs.

III. **Modelling and design of snapping morphing shells with curvilinear magnetically oriented reinforcements, journal paper:** Presentation of a modelling technique allowing curvilinear reinforcements to be design according to magnetic field positioning.

IV. **ICCM 2017, conference paper:** Initial numerical results on the topologies enabling large shape adaptation on Earwigs.

V. **SMASIS 2017, conference paper:** Numerical modelling and design of magnetically architectured snapping composites, expanding on the already studied bioinspired Venus Flytrap example.

6. Interactions/Transitions

6.1. Conference Proceedings and Presentations

I. H. Le Ferrand, A. R. Studart, A. F. Arrieta[3]***. Bio-inspired hierarchically structured snapping multifunctional composites.*** Materials Research Society (MRS) Fall Meeting, November 27th-December 2nd, 2016.

6.2. Completed Student theses

a. Student Name: Fiona Pacifico, Period of Thesis: 06.2015 - 08.2015
Thesis title: ***Investigating hydrogel matrix systems for bistable composite bilayers***
Supervisor: Prof. Andre Studart, Dr Andres Arrieta, Hortense Le Ferrand

b. Student Student Name: Florian Bär, Period of Thesis: 03.2015 - 07.2016
Thesis title: ***Shape adaptable epoxy films with alumina platelets reinforcement***
Supervisor: Prof. Andre Studart, Dr Andres Arrieta, Hortense Le Ferrand

c. Student Name: Thomas Peybernes, Period of Thesis: 03.2016 - 07.2016
Thesis title: ***Origami snapping Investigation of "flexible origami" for fast actuation of sheet-like materials***
Supervisor: Prof. Andre Studart, Dr. Kunal Masania

6.3. Planned interactions/Transitions next period

I. Internal interactions:

Post-doctoral visit: Dr. Hortense Le Ferrand will be visiting the group of Dr. Arrieta at Purdue between February 1st and May 31st. The aim of this visit is to transfer to Purdue-based students working under Dr. Arrieta the techniques and knowledge accumulated on the magnetically-driven design of functional composites. This interaction will also potentiate the collaboration by allowing mechanical testing of magnetically programmed structures at Purdue.

Post-doctoral visit: Dr. Jakob Faber plans to visit the group of Dr. Arrieta at Purdue between July to September to develop aeroelastically coupled models for the bioinspired programmable structures described in section 3.

[3] Presenting author

Annual Performance Report

This document presents the third technical report for the research grant **Fast morphing multi-stable structures made from shape-programmable bio-inspired composites**, with agreement number **FA9550-16-1-0007**, for the period of performance October 2017 to October 2018.

1. Objectives

The objectives of our research remain unchanged from those presented in the original proposal: This project aims to exploit the exciting possibilities for large shape reconfiguration and inherent sensing offered by programmable matter structures to realise radical geometric adaptation for bio-inspired morphing systems.

2. Status of Effort

In the third year of this project, we studied: I) Biological, multistable mechanism underlying snapping of the earwig wing and the ii) possibilities for sensing through changes of stable state in microstructured bistable composites, which results in biologically-inpired mechanosensing. In part (I) we studied the design principles of another biological structure that undergoes snapping: the wings of the earwig. The wings of the Earwig display three unique characteristics: largest change in wing area between a tucked in (stowed) and deployed configurations, self-locking on both configurations and fast deployment. These characteristics stem from a complex pattern of folds, that include curved crease lines. To understand this we, first, uncovered the underlying mechanism enabling these characteristics extending conventional origami theory. We proposed that creases were stretched in-plane, thereby allowing for crease lines to be curved and creating the bistable behaviour responsible of self-deployment/tucking, self-locking and fast morphing. Our *spring origami* theory was validated for the Earwig wing and utilized for creating simple compliant robotic grippers. In part (II), we exploited the expertise in magnetic alignment technology to produce microstructured multistable composites that exhibit magneto-elasto-electric coupling. We created microstructures that concurrently provided pre-stress fields leading to bistability, percolation networks of conductive particles, and magnetic responsiveness. The resulting artificial structures allow to create a threshold for filtering pressure inputs, measure a specified input level when it triggers snap-through to a second stable state, and to transmit the measured signal through a change in electric conductivity of the bistable structure. Furthermore, the magnetic coupling allows for resetting the bistable structure to its original configuration. This combination of sensory, filtering and conductivity change properties are similar to those displayed by mechanoreceptors in organisms with neural systems. More details about these projects are presented below.

3. Accomplishments/New findings

New origami theory enabling curved creases and modelling of the bistability of the Earwig wing was accomplished for the first time. This opens a completely new avenue for creating self-folding, self-locking and fast morphing in origami-based structures. Furthermore, as opposed to previous multistable origami demonstrators, our bioinspired spring origami allows to have completely rigid facets, while maintaining the desired properties stemming from bistability. This allows for utilizing conventional electronics and other systems that cannot undergo elastic deflections, as is necessary for most other multistable origami systems.

We also created new multistable structures exhibiting magneto-elasto-electric coupling that enable the use of shape to filter and measure external stimuli, while providing an intrinsic mechanism for transmitting sensory signals through changes in conductivity of the materials due to strain-activated percolation networks. These multistable mechanoreceptors mimic the behaviour of mechanoreceptors in neural systems. Our technique based on hierarchical microstructures is broadly

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material independent, needing only a conductive particle reinforcement in a matrix capable of modest pre-straining capabilities.

3.1. Research results

I. Biological, multistable mechanism underlying snapping of the earwig wing

The earwig uses a sophisticated, spring-loaded bistability mechanism for folding and unfolding its wing (see Fig. 1). It thereby achieves the highest ratio of folded to unfolded wing area in the animal kingdom. We numerically studied this folding process of the wing. The folding pattern could be successfully reproduced and biology literature was reviewed. We extended origami theory discovering that membrane strains in the creases were the key for creating the bistable behaviour in the Earwig wing, which is the responsible of its extraordinary properties. This spring origami theory is relevant for the development of a novel deployment mechanism for wings, solar panels and similar, faceted devices, as well as for soft robots and multistable surfaces as described below.

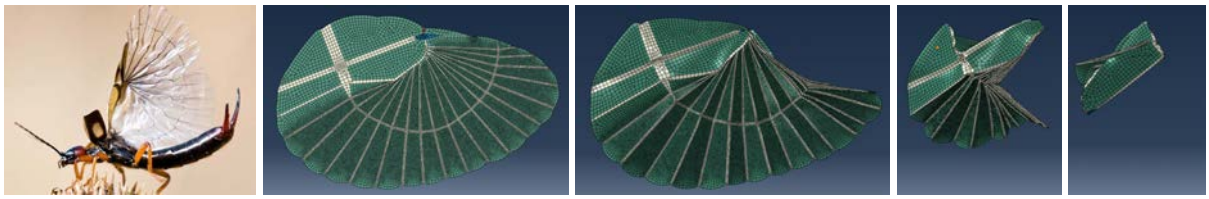

Fig. 1: Earwig wing example and numerically computed folding process

The manufacturing of the studied Earwig wing was conducted with multimaterial fused deposition modelling (FDM) to validate the modelling effort. FDM printing allows us to modulate stiffness in the range 0.1MPa to 5-10 GPa while working with polymers or partially-filled polymer systems. Our experiments have delivered proof of concept samples of the earwig wing, which was used to study extension-retraction as well as validate the modelling design approach (see Fig. 2). Our future efforts will focus on refining the manufacturing to yield actuating structures, and translate the designs into structural composite materials.

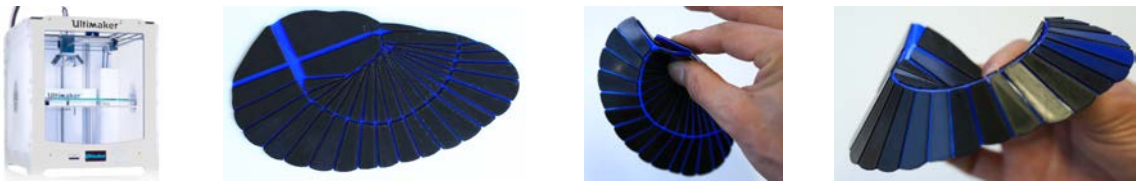

Fig. 2: First multimaterial prototypes produced by fused deposition modelling may be folded as the biological example (wing length 150 mm).

We extended conventional origami theory which had previously used bending energy in the facets and creases to explain multistability. We used the Earwig example and uncovered that the creases on its wings experienced in-plane (membrane) prestrain. Such prestrain was the responsible of the bistable characteristic of the wing, which in turn controlled the remarkable self-folding, self-locking on the deployed and folded states and the fast morphing observed in this insect order. We demonstrated this through finite element simulations, as described in Fig. 3. In addition to enabling multistability, our spring origami theory allows for the design of curved crease patterns. This opens up significantly larger design space and a novel avenue for achieving origami-inspired systems.

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We utilized the principles of the Earwig wing to create multifunctional structures exploiting the spring origami effect. First, we demonstrated the self-locking capacities attainable in systems with rigid facets (Fig. 4a). As explained above, attaining multistability in origami systems with rigid facets is important for applications for which stretching of components is not acceptable, e.g. with solar panels or conventional electronics. Secondly, we exploited the self-folding and self-locking behaviour to create a bistable gripper that conforms and holds objects of unknown shapes without the need of sensors or continuous actuation effort (Fig. 4b). This provides a novel pathway for creating compliant/soft robots with simplified sensory, actuation and control systems.

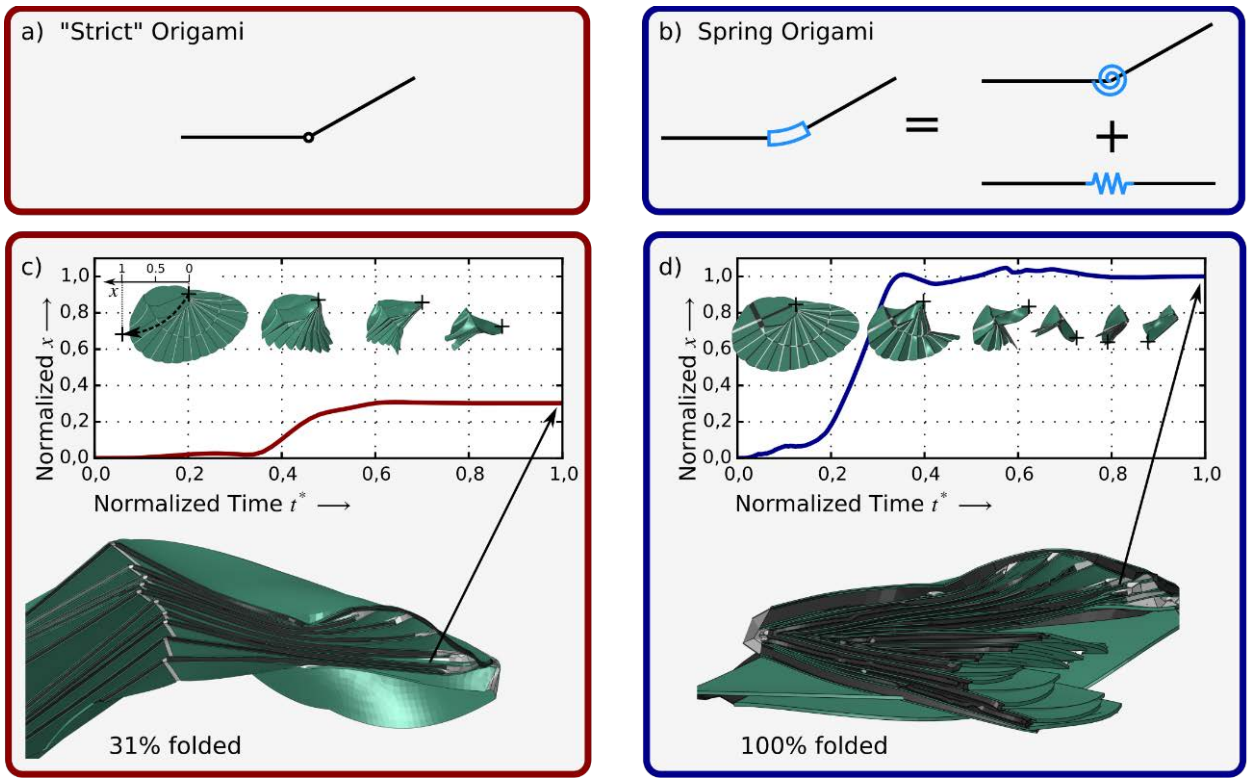

Fig. 3: Bioinspired spring origami theory. a) strict or rigid origami pin-joints. b) Spring Origami joints allowing for both rotational and extensional spring effects, and thus storage of both bending and membrane strain energies on creases. c) Simulation of Earwig wing closing with strict origami theory, showing the failure to capture the full closing of the Earwig wing under conventional assumptions. d) Simulation of Earwig wing closing using spring origami theory. Full wing closure is attained.

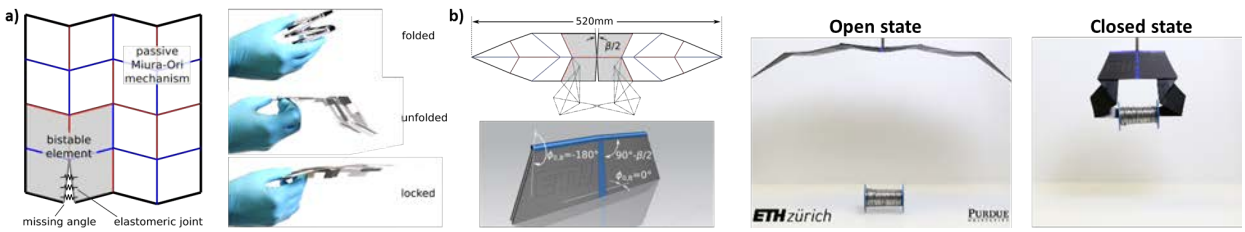

Fig. 4: Applications of bioinspired spring origami. a) Self-locking rigid facet multstable surface. b) Bistable spring origami gripper.

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II. Mechano-sensing bistable composites

The key fundamental novelty in this part of the research project was the creation of composites with fast, passive and filtered mechano-sensing capabilities directly programmed within their hierarchical structure. Similar to the mechano-sensing systems evolved in living organisms, our large and stiff conformable composites rely on multiphysics couplings at the material's level, thereby providing intrinsic filtered sensing, communication and computation capabilities at the same time as structural functions.

Although extensive work has been reported on fast and passive sensing, most developed technologies rely on micro- or nano- soft devices limiting the range of possible external stimuli and posing a data processing challenge in dense sensing networks. A very recent work developed by our team demonstrated how mechanical bistability can arise in composite laminates containing discontinuous micro-reinforcements. We leveraged this discovery to bridge the mechanically-triggered change in shape with a variation in electrical conductivity. This allows for a direct and passive translation of mechanical forces into a signal usable by a computer brain.

The scientific breakthrough underlying this new concept is the control of the macroscopic parameters of the filtering sensor by the microstructural architecture of the composite, much like in natural materials. The perpendicular alignment of ceramic anisotropic particles in a bilayer of thermoset epoxy provides bistability and fast, passive and filtered mechanical sensing by a change in shape. Small amounts of ferromagnetic anisotropic flakes co-aligned with these particles create a binary electrical signal representative of the mechanical state. To this electrical conductivity is added a magnetic susceptibility that enables the triggering of the change in shape remotely by a magnet. The fabrication process is highly tunable in composition, geometry, and dimensions to adapt to large and complex structures. Furthermore, we achieved proof-of-concept examples that these mechano-sensors can be readily integrated into electrical circuits for computation and combined in arrays for large network sensing. A schematic illustration of our mechano-sensing composites and the biological counterparts that inspired this work are shown in Fig. 5.

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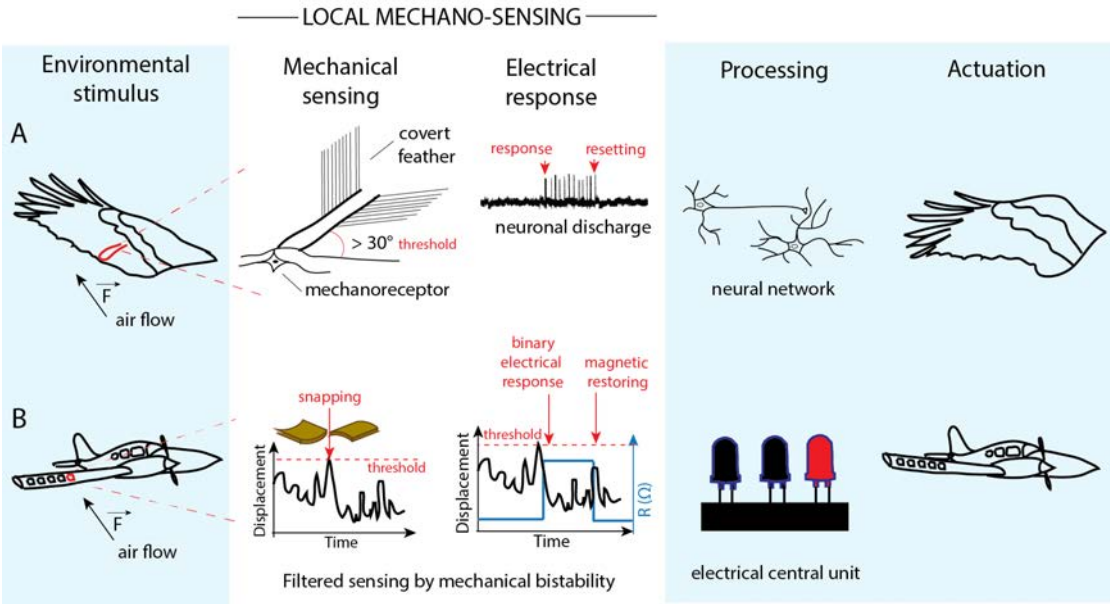

Fig. 5. Schematics describing the sensing and actuating principles of the wing of birds (A) and the bioinspired concept of bistable mechanosensing developed in our study (B). (A) Under airflow, the deflection of covert feathers of birds above a threshold of ~30° triggers a neuronal electrical discharge, which is further processed by the neuronal network to appropriately actuate the shape of the wing. The signal is reset after the input air flow ceases. (B) In the bioinspired analogue, a bistable mechanosensor could be used to monitor the airflow across the wing of an aircraft. When the air flow is sufficient to snap the bistable sensor, a change in electrical conductivity is detected. This electrical signal can be further processed through a central unit to provide the relevant actuation of the wing of the plane. Resetting to the initial condition is possible by applying a magnetic field.

4. Personnel Supported

Dr. Jakob Faber has been involved in the project from October 2016 until September 2018. He focused on discovering novel structural topologies enabling the large reconfiguration of morphing systems drawing inspiration from biological examples. Dr. Faber worked closely with Prof. Andres F. Arrieta from Purdue University, where he visited during Summer 2017.

5. Publications

5.1. Conference proceedings

I. K. S. Riley, H. Le Ferrand, *A. F. Arrieta*. ***Modeling of bio-inspired, snapping composite shells with magnetically aligned reinforcements.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2017), Snowbird, Utah, USA, September 18 – 20, 2017.

II. K. J. Ang, K. S. Riley, J. Faber, *A. F. Arrieta* ***Switchable bistability in 3D printed shells with bio-inspired architectures and spatially distributed pre-stress.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2018), San Antonio, Texas, USA, September 10 – 12, 2018.

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Best student paper ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2018)

5.2. Journal papers: Published

I. J. Faber, A. F. Arrieta, A. R. Studart. ***Bioinspired spring origami***. Science, 359(6382), 1386-1391, 2018. https://doi.org/10.1126/science.aap7753

II. K. S. Riley, H. Le Ferrand, A. F. Arrieta***. Modeling of snapping composite shells with magnetically aligned bio-inspired reinforcements.*** Smart Materials and Structures, 21(11), 114003, 2018. https://doi.org/10.1088/1361-665X/aad797

5.3. Journal papers: Under review or in preparation

III. H. Le Ferrand, A. R. Studart, A. F. Arrieta. ***Nanostructured hierarchical composites for filtered mechano-sensing.*** ACS Nano, 2019. Under review.

IV. K. J. Ang, K. S. Riley, J. Faber, A. F. Arrieta. ***Switchable Bistability: Multiple Shape Programming Exploiting Elastic Strain from 3D Printing and Phase Transition.*** 2019. In preparation.

6. Interactions/Transitions

6.1. Conference Proceedings and Presentations

I. *A. F. Arrieta*, J. Faber, K. S. Riley, A. R. Studart. ***Extending origami: crease pre-stressing for functional adaptation.*** IUTAM Symposium Architectured Materials Mechanics, September 17-19, 2018, Chicago, IL.

II. K. S. Riley, *A. F. Arrieta*. ***Bio-inspired distributed pre-stress from magnetically aligned microstructures for fast morphing.*** 4th Midwest Mechanics of Materials and Structures workshop, Illinois Institute of Technology, Chicago, August 4, 2018.
Third-place award in poster presentation

III. K. S. Riley, H. Le Ferrand, *A. F. Arrieta.* ***Use of bio-inspired programmable materials to achieve fast morphing shells with desired deformations.*** 28th International Conference on Adaptive Structures and Technologies (ICAST), Cracow, Poland, October 8 – 11, 2017.

IV. J. Faber, *A. F. Arrieta*, A. R. Studart. ***Learning from the earwig wing: a bioinspired approach towards fast morphing structures using multistability***. 21st International Conference on Composite Materials (ICCM), Xi'an, China, August 20 – 25, 2017.

6.2. Planned interactions/Transitions next period

I. Internal interactions:

Research visit: Dr. Arrieta visited ETH Zurich several times during the period 2017-2018. A final research visit is planned for spring/summer 2019.

II. Internal within "Muscular-Skeletal System Inspired Morphing Air Vehicles Using Active Materials"

Presentations included:

- Fast Morphing Multi-stable Structures Made from Shape Programmable Bio-inspired Composites, BRI meeting, London, March 2017.
- Fast Morphing Multi-stable Structures Made from Shape Programmable Bio-inspired Composites, BRI meeting, Stanford University, March 2018.

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6.3. Honours and Awards

I. Best student paper ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2018), San Antonio, TX, 2018.

II. Third-place award in poster presentation in the 4th Midwest Mechanics of Materials and Structures workshop, Illinois Institute of Technology, Chicago, August 4, 2018.

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