

Pneumatically Actuated Material

Lynn Kieffer
CITAstudio / Royal Danish
Academy of Fine Arts

Paul Nicholas
CITA / Royal Danish Academy
of Fine Arts

Exploration of the Morphospace of an Adaptable System of Soft Actuators



1

ABSTRACT

This research in progress investigates a design and fabrication method of an adaptable and programmable composite material in an embodied computation system. It develops a workflow for a behavior-based model, the exploration of the morphospace associated with the combinatorial assembly, and the actuation of soft elements. The aggregation of individually actuatable and soft units in a system creates a large potential for adaptability, flexibility, and reconfigurability through a non-rigid and non-mechanical system. The cells are developed through a process of prototyping on origami- and auxetic pattern-inspired soft robotic elements. Every soft cell is pneumatically actuated through a negative pressure environment. The computational simulation is informed by the prototyping process and its findings. The simulation-based design of such an assembled system allows prediction of the aggregated shape and outputs a sequencing table describing the actuation status of every cell, and can create a tool to communicate between material and computational systems.

- 1 Assembly of actuatable soft element
- 2 First probes, exploring different shape-shifting characteristics, linked to their pattern. The first and third row show the elements in non-actuated state, the second and fourth demonstrate the deformation through actuation.

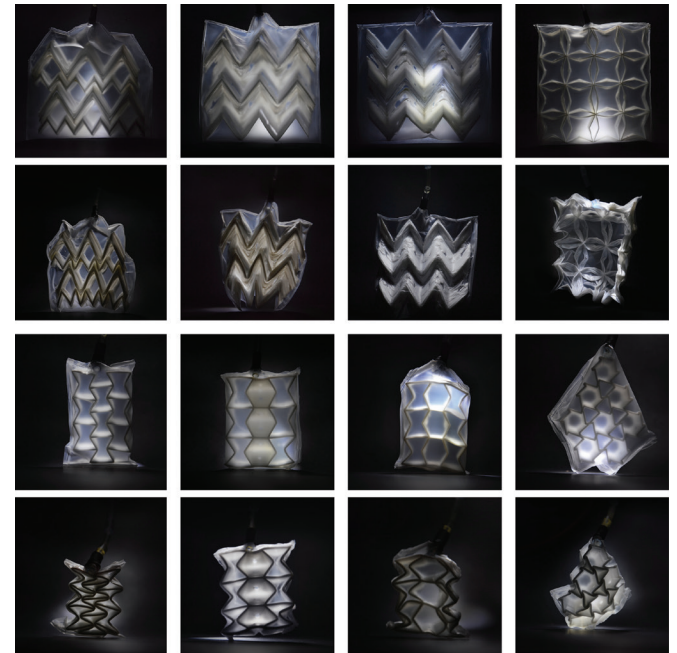
INTRODUCTION

The interest in adaptability and responsivity of architecture is steadily growing. Kinetic design approaches search for acoustically or spatially shifting solutions (Decker 2015; Osório, Paio, and Oliveira 2014), among other things, and most—exemplified by Chuck Hoberman's Iris Dome—deploy a mechanical method of kinetic actuation. However, mechanical systems like this have a limited range of flexibility.

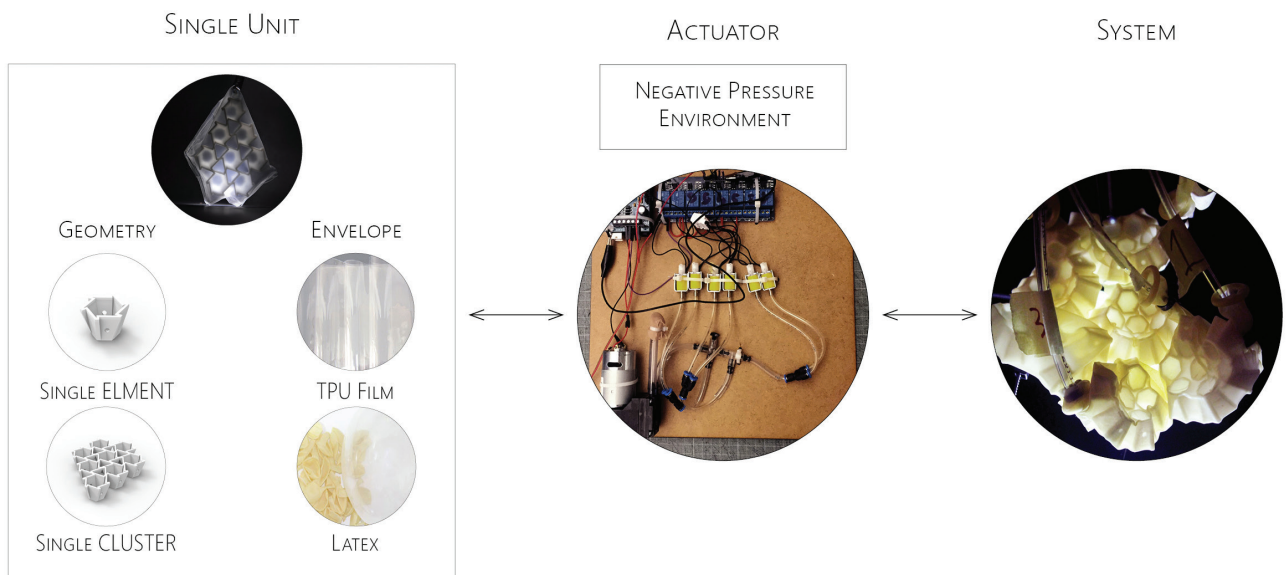
This work in progress is situated in the context of responsive and adaptive architecture (Menges et al. 2013; Beites 2013; Li, Shang, and Wang 2017) and soft robotics (Polygerinos et al. 2015; Deshpande, Tse, and Ren 2017; Decker 2015). It explores the morphospace of a combinatorial system of soft actuators that are actuated individually through a negative pressure environment and deploy a mechanical jamming mechanism (Li, Shang, and Wang 2017; Deshpande, Tse, and Ren 2017). Most commonly, combinatorial systems provide a method for assemblies of rigid elements. However, in systems such as Smart Granular Materials (Dierichs et al. 2017) or PneuSystems (Velikov, Thün, and O'Malley 2014), the actuation of single elements is deployed as a method of entanglement and interlocking of units.

In this research, the local deformation of a unit through actuation leads to a global change of shape. The soft machines are not applied as fabrication or construction tools in architecture, but instead become architecture themselves (Kilian and Sabourin 2017; Thomsen et al. 2015; Alquist, McGee, and Sharmin 2017). The softness of the

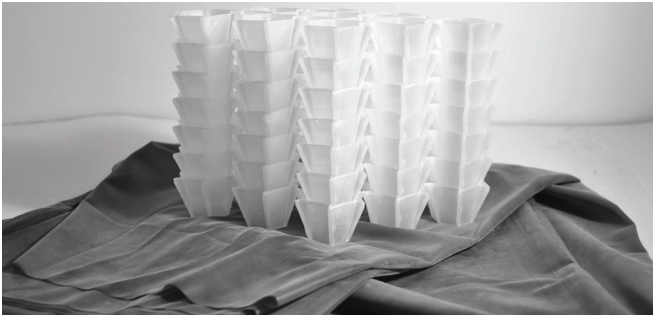
material not only characterizes the flexibility of the single unit in the non-actuated state, but also implies the smooth transition between different actuation states. The use of discrete elements offers the possibility of reconfigurability, customization, and recycling of the whole through assembly and disassembly. In this research project, the information from the physical world and its behavior are undeniable for computing outcomes, which can be referred to as embodied computation. The individual programmability of the actuation state of every single unit in the system allows a large range of overall deformation possibilities, which is explored digitally through a spring-based simulation and physically



2



3 Outline of the adaptable system as an assembly of single elements.



4



5

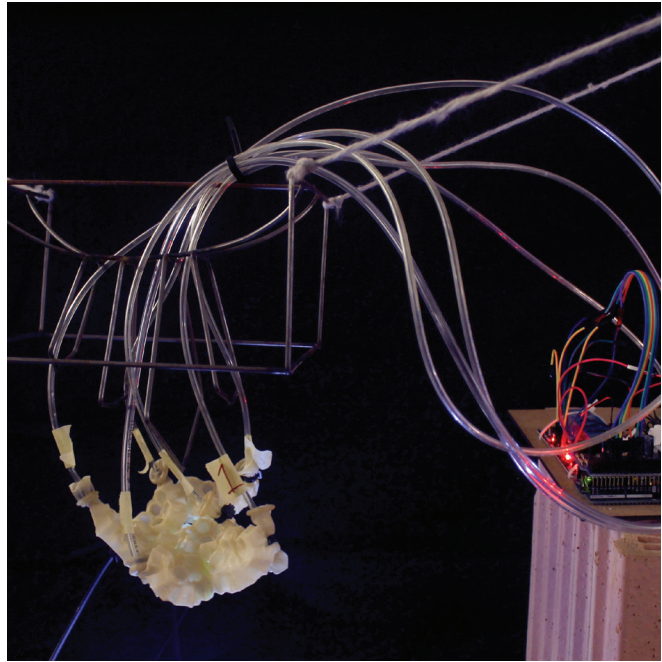
on a prototype. This computational method is controlled by a sequencing table that informs the actuation state of every single cell in this aggregation.

BACKGROUND

While current conceptions of robotics in architecture privilege the idea of robotic fabrication and industrial robot arms, the potential goes far beyond making (Kilian and Sabourin 2017; Kim et al. 2015; Abramovic, Glynn, and Achten 2017).

Smart Materials

Architecture can react to certain requirements through environmentally activated materials, such as heat- or humidity-actuated materials. (Addington and Schodek 2005; Menges 2013). In the world of smart materials, there has been a particular focus on material systems that exhibit bidirectional behavior. Shape-memory polymers (SMP), which have until now been mainly examined in the field of biomedicine and aerospace, have kinetic dual-shape qualities and expand or contract in a linear way when exposed to heat (Beites 2013). Additive-layered manufacturing technologies using those dual-shape materials are specified as 4D printing. The material composition allows a customized and programmable deformation of a surface through external stimuli (Li, Shang, and Wang 2017). Volumetric dual-shape materials can be introduced as phase changing materials, where design methods can control their behavior (Faircloth et al. 2018).



6

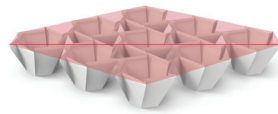
Soft Machines

This research looks at pneumatically actuated soft elements as an alternative or complement to the above approaches of shape-shifting materials.

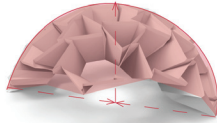
Large-scale pneumatic objects have already been explored since the 1960s. Study objects such as the Yellow Heart or the Instant City (Archigram 1968), or newer buildings such as Tubaloon (Snøhetta 2016) or the Allianz Arena (Herzog de Meuron 2005) demonstrate the structural, thermal, and acoustic isolating and lightweight qualities of pneumatics in architecture.

In the world of robotics, soft actuators, which are mainly monolithic elements, explore necessities like flexibility, adaptability, and safety requirements in the interaction between human and robot (Polygerinos et al. 2015; Deshpande, Tse, and Ren 2017; Decker 2015). They oppose the rigidity of mechanic robotic components and can shift shape (Polygerinos et al. 2015; Decker 2015). Pneumatic and hydraulic soft robotic components are often favored due to their lightweight, low-cost, and power-to-weight ratio qualities. (Polygerinos et al., 2015)

In the last years, a novel method of soft actuation has emerged. This method combines origami-inspired folding methods using a non-expandable material and a pneumatic envelope, enclosing the folded object (Deshpande, Tse, and Ren 2017; Li, Shang, and Wang 2017). The single unit is actuated through a jamming mechanism that stiffens in a negative pressure environment by "jamming" the material



SINGLE UNIT
NON-ACTUATED



SINGLE UNIT
ACTUATED

7

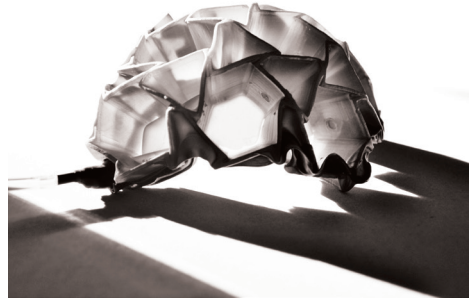


- 4 3D-printed clusters before wrapping.
- 5 Actuated probe, demonstrating spatial deformation
- 6 Small-scale assembly of units, partially actuated.
- 7 Digital simulation of a single unit.

8

- 8 Skeleton and envelope for one single unit.

- 9 Actuated state of a single physical unit.



9

inside the pneumatic pocket together. The usually granular material inside the pneumatic actuator is here exchanged with a pocket attached, origami-folded element. Every unit has one actuation source controlling its dual-shape behavior.

METHOD

This research connects physical and digital methods so that one informs the other. We have gained an understanding of the making and physical performance of the system by producing a range of differently patterned probes. The behavior of one chosen pattern was selected to calibrate a digital simulation approach capable of accurately describing the behavior of assemblies of this element. This combined digital and physical approach supported the exploration of morphospace associated with different assemblies and their shift in shape according to certain sequencing patterns.

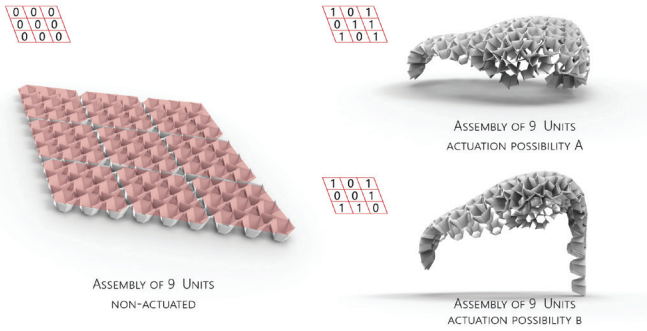
Prototyping Process

The physical sample has evolved from a series of probes exploring geometrical changes in a state of actuation. One single cell is composed of a flexible but non-extendable three-dimensional geometry and a pneumatic enclosing envelope. Those single units are actuated through a negative pressure environment around the pneumatic hull, and in later stages are joined together in a system of multiple elements. The deformable geometry of every unit is a cluster of several identical elements arranged in two dimensions and linked through flexible hinges. The deformation grade of the single unit can be controlled through

its wall thickness and hinge size. The prototypes showed, that hinges of 1.0 mm wall thickness created the highest deformation results when actuated for small-scaled units around 60 to 220 mm in diameter. To improve the airflow through the extruded pattern, small holes were placed in the walls of each element. These units are printed using a fused deposition modelling (FDM) method with a flexible TPU material, which can't expand while the unit is deformed.

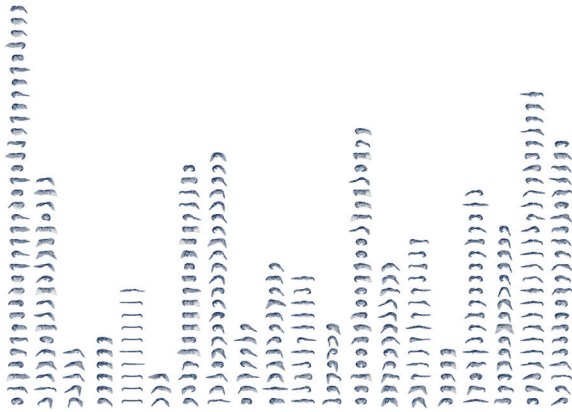
Several pattern studies have been conducted, experimenting with mechanical metamaterial, such as auxetic formations and origami-inspired geometries. Mechanical metamaterials are artificial materials that, unlike other adaptive materials, don't show shape-changing characteristics through material composition, but rather through geometry and structure (Mesa et al. 2017). Regular patterns, such as the negative Poisson ratio sample, showed full contraction in actuated state. If, however, a column of convex elements is added in between the concave ones, the contraction of those is drastically diminished. However, spatial shape shifting through geometrical characteristics, such as triangular patterns and tapered geometries, showed more potential for this research than linear or two-directional deformations.

An airtight envelope encloses the deforming geometry, which in actuated state forces the geometry into its deformed state. The envelope is in no point attached to the geometry—it is only enclosing it. Envelope size tests showed that envelopes with loose fit enable the best deformation results, whereas exceedingly large hulls



10

hinder airflow through the cell. The first experiments have been conducted using a soft and translucent TPU film. The custom airtight pocket has been created using an ultra-sonic hand welder. The best outputs resulted when folding the material before welding it. Although the material is soft, it extends while actuated and is unable to retract to its starting size, and is thus not convenient for these explorations. The material used for those elements needs to be elastic and fully retractable after actuation. For this application, a better solution can be found in a natural latex sheet, since it is perfectly airtight and can have customized pockets created through sealing with liquid latex. In addition to the required characteristics of the material, latex introduces visual qualities through opacity shifts.



11

The fully assembled pneumatic unit is actuated through the application of a negative pressure environment using a 12 V power source. The individual controllability of every cell introduces an adaptable system. The pneumatic cells (geometry and pocket) are joined through soft hinges. The assembly works as one single system and needs the units to be joined as one surface. This requires connections on the top and bottom of the units. Those connections are soft and allow the unit to deform when actuated. However, they are non-extendable and force their non-actuated neighbors into a passive deformation. Latex loops are reinforced with a sewing pattern and a stretchable textile. The seam controls the extension if forces are applied on the loop and the textile prevents it from ripping.

Digital Model and Simulation

A digital simulation of the unit and its assembly in a system of actuatable cells has been generated using the spring-based simulation engine Kangaroo2 (Piker 2015). As in the physical prototyping phase, the simulation of the single cell has been generated first. For this a spring-based model representing one symmetric unit of nine tapered hexagonal geometries imitates the deformation of the physical model. This actuatable unit is then assembled in regular and irregular lattices, where every cell can be individually controlled and influences its neighbors when in an actuated state..

Exploring the Morphospace

The exploration of the morphospace is conducted on the digital and physical model. It investigates the possible shapes of regular and irregular planar lattices containing several identical cells. Every shape is created through a table of sequences that define the actuation state of every single unit in the system as generated by an evolutionary solver. This table of sequences is then implemented into the digital model and informs its unit's actuation state. As the cells are arranged in the same way as in the digital model and follow

12

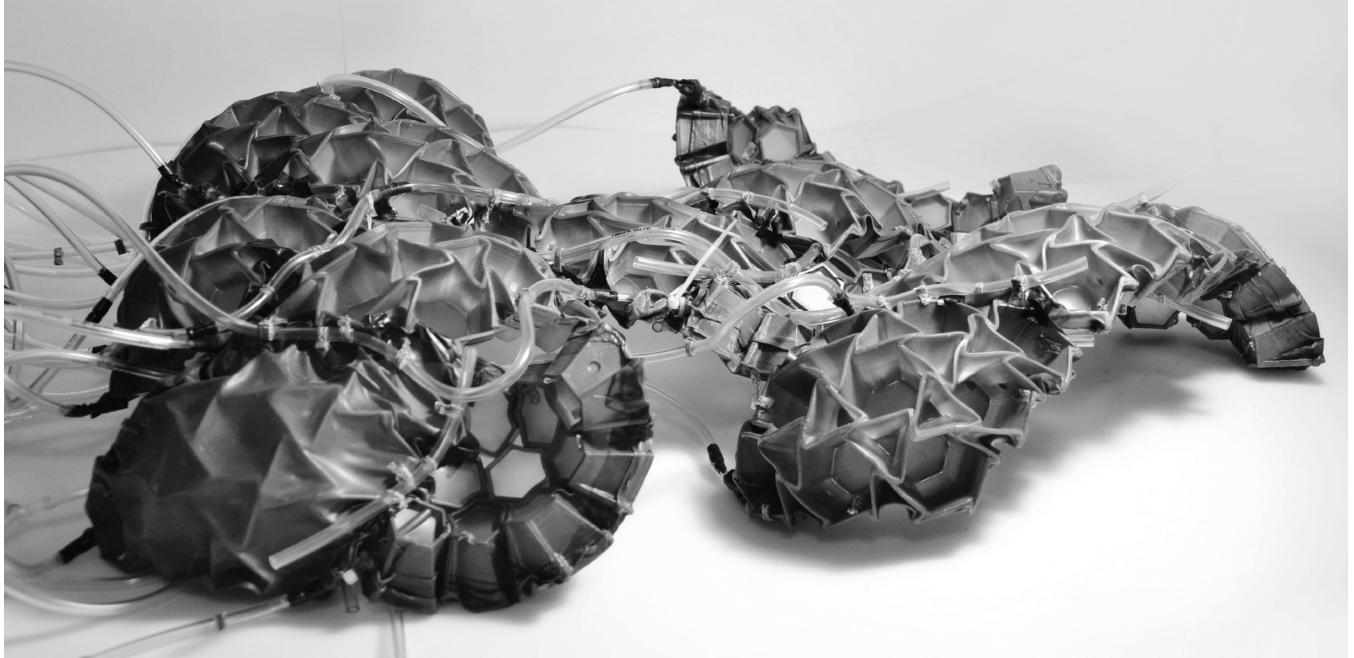
10 Digital simulation informed through sequencing tables of the same topology.

11 Exploration of the morphospace of a regular lattice (same topology).

12 Digital simulation informed through sequencing tables of an irregular lattice.

14 Small assembly of three units, demonstrating the passive deformation of a non-actuated cell.

15 Small assembly of actuated units.



13 Prototype and investigation of its shape-shifting qualities on a global and local level.

the sequencing table, thus informing the orientation state of every unit, the behavior of the digital object can be adjusted according to the physical assembly. The unsupervised learning algorithm (*k*-means clustering) has then been used to categorize those generated digital models by descriptive parameters.

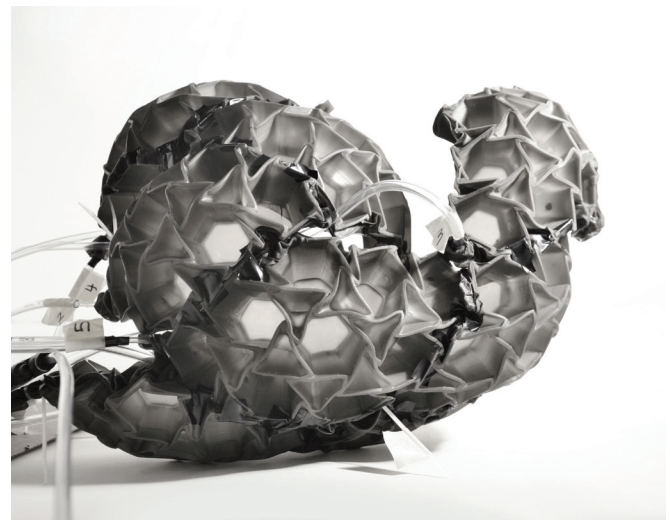
RESULTS

Small assemblies led to very successful results, proving that a large range of different shapes can be created from one single topology. Actuated units passively deform their neighbors and influence the model at both a local and global level. However, if the number of assembled units increases, the overall weight hinders a predicted deformation. The texture of the latex seems to be too smooth and the 5 mm wide connections start to loosen. In subsequent explorations, this connection problem needs to be investigated and solved to allow further development of this research.

Simulation gives us a tool to speculate on design and behavior; however, as this research shows, the predicted cases don't always accord to the physical element. A lack of information about materiality and behavior input only allows us to approximate physical and digital behavior. In future phases, 3D scanning could be involved to understand the discrepancy between the digital and physical world. In addition to the informative level, the scanning method could create a higher level of bidirectionality in the model. Whereas now the human being plays an indispensable role in the communication between digital and physical components, this method could take over the role of evaluating



14



15

them, and a stronger interaction among model, environment, computational simulation, and human could be achieved.

CONCLUSION

This research establishes a workflow for the fabrication and design of an adaptable intelligent system, which can lead to a communication tool between the physical and computational artefact. The assembly of soft actuated elements as building material challenges the possibilities of soft robotics and their application in the field of architecture as smart materials. While these materials usually deform due to their material composition, here the proposed assembly of pneumatic units offers a larger range of freedom in scale and shape, since the deformation is programmed through the system's geometry, as well as its additive and reconfigurable nature.

In further explorations, the prediction of every shape based on tables of actuation sequences can be developed as a tool to inform and train the physical material and generate real-time communication and adaptation. An intelligent material could emerge that is able to adapt and respond to certain architectural needs and suggest new spatial formations. While the softness of the architecture can respond to acoustic and spatial comfort, the change in translucency of the shape-shifting material suggests light-related qualities.

ACKNOWLEDGEMENTS

This paper presents a semester research project developed by Lynn Kieffer at CITAstudio at the Royal Danish Academy of Fine Arts, under supervision of Prof. Paul Nicholas. The authors would like to thank Hannah Arkell, Jens Lee and Viktoria Millentrupp, who helped gather development ideas during a one-week workshop led by Mette Ramsgaard Thomsen at CITAstudio.

REFERENCES

- Abramovic, Vasilija, Ruairi Glynn, and Henri Achten. 2017. "Roamniture; Multi-Stable Soft Robotic Structures." In *ShoCK!: Sharing Computational Knowledge!—Proceedings of the 35th eCAADe Conference*, vol. 1, edited by A. Fioravanti, S. Cursi, S. Elahmar, S. Gargaro, G. Loffreda, G. Novembri, and A. Trento, 327–36. Rome: eCAADe.
- Addington, D. Michelle, and Daniel L Schodek. 2005. *Smart Materials and Technologies*. London: Architectural Press.
- Ahlquist, Sean, Wes McGee, and Shahida Sharmin. 2017. "Pneumaknit: Actuated Architectures Through Wale- And Course-Wise Tubular Knit-Constrained Pneumatic Systems." In *Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, edited

by Takehiko Nagakura, Skylar Tibbits, Mariana Ibanez, and Caitlin Mueller, 38–51. Cambridge, MA: ACADIA.

Beites, Steven. 2013. "Morphological Behavior Of Shape Memory Polymers Toward A Deployable, Adaptive Architecture." In *Adaptive Architecture: Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Philip Beesley, Omar Khan, and Michael Stacey, 121–8. Cambridge, ON: ACADIA.

Decker, Martina. 2015. "Soft Robotics And Emergent Materials In Architecture." In *Real Time: Proceedings of the 33rd International Conference on Education and Research in Computer Aided Architectural Design in Europe*, vol. 1, edited by Bob Martens, Gabriel Wurzer, Thomas Grasl, Wolfgang El. Lorenz, and Richard Schaffranek, 409–16. Vienna: eCAADe.

Deshpande, Ajit R., Zion Tsz Ho Tse, and Hongliang Ren. 2017. "Origami-Inspired Bi-Directional Soft Pneumatic Actuator With Integrated Variable Stiffness Mechanism." In *Proceedings of the 18th International Conference on Advanced Robotics*, 417–21. Hong Kong: ICAR.

Dierichs, K., Wood, D., Correa, D. and Menges, A. 2017. "Smart Granular Materials: Prototypes for Hygroscopically Actuated Shape-Changing Particles." In *Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Takehiko Nagakura, Skylar Tibbits, Mariana Ibanez, and Caitlin Mueller, 222–31. Cambridge, MA: ACADIA.

Faircloth, Billie, Ryan Welch, Yuliya Sinke, Martin Tamke, Paul Nicholas, Phil Ayres, Mette Ramsgaard Thomsen, and Erica Eherenbard. 2018. "Coupled Modeling And Monitoring Of Phase Change Phenomena In Architectural Practice." In *Symposium On Simulation for Architecture + Urban Design*. Delft, the Netherlands: SimAUD.

Kilian, Axel, and François Sabourin. 2017. "Embodied Computation - An Actuated Active Bending Tower: Using Simulation-Model-Free Sensor Guided Search To Reach Posture Goals." In *Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Takehiko Nagakura, Skylar Tibbits, Mariana Ibanez, and Caitlin Mueller, 324–9. Cambridge, MA: ACADIA.

Kim, Simon, Mark Yim, Kevin Alcedo, Mike Choi, Billy Wang, and Hyeji Yang. 2015. "Soft Robotics Applied To Architecture". In *Computational Ecologies: Design in the Anthropocene, Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Lonn Combs and Chris Perry, 232–42. Cincinnati, OH: ACADIA.

Krauel, Jacobo. 2013. *Inflatable: Art, Architecture & Design*. Barcelona: Links.

Li, Shuguang, Daniel M. Vogt, Daniela Rus, and Robert J. Wood. 2018. "Fluid-driven Origami-Inspired Artificial Muscles." *Proceedings of the National Academy of Sciences of the United States* 114 (50): 13132–7.

Li, Xin, Jianzhong Shang, and Zhuo Wang. 2017. "Intelligent Materials: A Review Of Applications In 4D Printing." *Assembly Automation* 37 (2): 170–85. doi:10.1108/AA-11-2015-093.

Menges, Achim, David Correa, Oliver David Krieg, Steffen Reichert, and Katja Rinderspacher. 2013. "Hygroskin: A Prototype Project For The Development Of A Constructional And Climate Responsive Architectural System Based On Elastic And Hygroscopic Properties Of Wood." In *Adaptive Architecture, Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Philip Beesley, Omar Khan, and Michael Stacey, 33–42. Cambridge, ON: ACADIA.

Mesa, Olga, Milena Stavric, Saurabh Mhatre, Jonathan Grinham, Sarah Norman, Allen Sayegh, and Martin Bechthold. 2017. "Non-Linear Matters: Auxetic Surfaces." In *Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by Takehiko Nagakura, Skylar Tibbits, Mariana Ibanez, and Caitlin Mueller, 392–403. Cambridge, MA: ACADIA.

Osório, Filipa, Alexandra Paio, and Sancho Oliveira. 2018. "Kos-Kinetic Origami Surface." In *Rethinking Comprehensive Design: Speculative Counterculture, Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia*, edited by Ning Gu, Shun Watanabe, Halil Erhan, Matthias Hank Haeusler, Weixin Huang and Ricardo Sosa, 201–10. Kyoto: CAADRIA.

Thomsen, Mette Ramsgaard, Martin Tamke, Phil Ayres, and Paul Nicholas. 2015. *CITAWorks*. Toronto: Riverside Architectural Press. 178

Polygerinos, Panagiotis, Zheng Wang, Johannes T. B. Overvelde, Kevin C. Galloway, Robert J. Wood, Katia Bertoldi, and Conor J. Walsh. 2015. "Modeling of Soft Fiber-Reinforced Bending Actuators." *IEEE Transactions On Robotics* 31 (3): 1565–76.

Velikov, Kathy, Geoffrey Thün, and Mary O'Malley. 2014. "PneuSystems: Cellular Pneumatic Envelope Assemblies." In: *Design Agency, Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by David Gerber, Alvin Huang, and Jose Sanchez, 435–44. Los Angeles: ACADIA.

IMAGE CREDITS

All drawings and images by the authors.

Lynn Kieffer is currently enrolled at the Royal Danish Academy of Fine Arts, in "CITAstudio: Computation in Architecture" Master Program. She holds a B.Sc. in Architecture from the University of Innsbruck. Lynn has worked as an assistant teacher in Innsbruck and has been a student assistant at the Centre for Information Technology and Architecture, CITA at the KADK Copenhagen, Denmark.

Paul Nicholas holds a PhD in Architecture from RMIT University, Melbourne, Australia. He is an Associate Professor at the Centre for Information Technology and Architecture (CITA), KADK Copenhagen Denmark and head of the CITAstudio: Masters in Computation international masters programme. Paul has previously practiced with Arup Engineers from 2005 and AECOM/Edaw from 2009. Paul's research interests lie in the development of innovative computational approaches that extend architecture's scope for design by establishing new bridges between design, structure, and materiality. His recent research explores sensor-enabled robotic fabrication, multiscale modeling, and the idea that designed materials such as composites necessitate new relationships between material, representation, simulation, and making.



16 Small assembly of actuated units.