ROAMNITURE

Multi-Stable Soft Robotic Structures

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The rise in robotics is not only changing fabrication research in architecture but increasingly providing opportunities for animating the materiality of architecture, offering responsive, performative and adaptive design possibilities for the built environment. A fundamental challenge with robotics is its suitability to safe, and comfortable use in proximity to the human body. Here we present the preliminary results of the Roamniture Project, a hybrid approach to developing kinetic architecture based on a combination of rigid and soft body dynamics.

Keywords: *Kinetic Architecture, Soft Robotics, Soft Architecture, Furniture*

INTRODUCTION

Robotics are not just changing fabrication in architecture but increasingly providing opportunities for animating the materiality of architecture offering responsive, performative and adaptive design possibilities for the built environment. A fundamental challenge with robotics is their suitability to safe, and comfortable use in proximity to the human body. Industrial mechanical principles with rigid-body dynamics characterised early exploration of Kinetic Architecture such as Frederick Kiesler's Raumbühne (space stage, 1924), or Vladimir Tatlin's Monument to the Third International (1919-20). Later Archigram imagined Walking Cities (Cook 2009) and Cedric Price the Fun Palace (Price 1968) and today we are seeing the realisation of some of these ideas in Diller Scofidio + Renfro The Shed [5] project opening in 2019.The approach to the transformability of The Shed, borrows from industrial rigid-body dynamics and the traditions of theatre rigging being able to expand and contract by rolling the telescoping shell on rails. Transformations occur out of reach of the public. Similarly, Chuck Hoberman's Iris Dome (Kassabian et al 1999) elevates his expanding mechanisms up out of reach as a transforming roof. Furthermore, a variety of projects in recent years have investigated building envelope surface transformations e.g. Bloom by DO|SU Studio Architecture (2012) (Orhon 2016), Ned Khan's kinetic wind responsive facades (Ryu et al. 2015) or Al Bahar Towers responsive facade (Elghazi et al. 2014) in Abu Dhabi which feature actuated solar system attached to the rigid structure. What these examples point to is that many popular examples of kinetic architecture are characterised by rigid-body principles, and do not address an architectures direct material relationship to inhabitants bodies and their movement.

Soft Architecture

Looking towards softer kinetics we were drawn first to architectures pneumatic experimentation of the 1960s were inflatables critiqued the hardness and inflexible forms of modernism. Architects such as J.P. Jungmann and his Dyodon (1968) (Pauletti, et al. 2005) project for pneumatic dwelling environment, or Jose Miguel de Prada Poole and project La Casa Jonás (1968) [2] developed proposals for dwellings principally reliant on complex inter-connect inflatable cushions. Meanwhile Austria architects Haus-Rucker-Co and Coop Himmelb(l)au through provocative installations begun to test the feasibility of a radically soft architecture. Coop Himmelblau's motto was 'an architecture that is as variable as a cloud' (Noever 2007) and appropriately so they have built many installations that expressed this idea in early 70s and 80s. Projects such as Villa Rosa (1968), Wolke- The Cloud (1968), Herz Stadt - der weisse Anzug - Heart City - the white suit (1969), exploring transformable, volume changing pneumatic structures and 'the possibilities of technology as a "natural" extension of the body' (Vidler 2000).

In the UK, Mark Fisher, studying under Peter Cook at AA introduced a series of pneumatic experiments as a way of real time space response to user's requirements, by expansion and contraction of its pneumatic structure. Projects like Automat (1968), Dynamat (1969-72) (Mullen 2014) and Responsive Dwelling Project (1973-75) demonstrate Fisher's fascination with dynamically changeable pneumatic structures. Similar ideas are found in Sean R. Wellesley-Miller projects done at MIT - Prototype of 'air-coil-system' (1971) and Prototype of 'binary cell system' (1971). Ant Farm, a radical architecture collective based in Berkeley, California, issued the Inflatocookbook (1971), a guide to the construction and realization of inflatable architecture, and presented many projects such as Clean Air Pod (1970) and Pillow (1970) (Lewallen et al. 2004). Frei Otto who demonstrated his research explorations in the 1970s, later came to be the inspiration to pneumatic motion and soft systems of contemporary architects to follow. He presented 'Motion sequence of pneumatic studies with tension bands' in 1979, where he discussed hydroskeleton of caterpillars, worms and other animals.

Negroponte's seminal publication Soft Architecture Machine (1975) (Negroponte 1975), stated that soft materials, such as inflatable plastics, were at the moment the most natural material for responsive architecture. His notion of softness however extended into thinking about the softness of systems as well as materials and lay the intellectual basis for responsive architecture research such as that produced at the Hyperbody group at TU Delft led by Kas Oosterhuis. Hyperbody has shown projects such as E-motive House (2002), NSA Muscle (2003) and Muscle-Body (2005) (Oosterhuis et al. 2004). In 2006 Michael Fox et al, built Bubbles (Fox 2009), an interactive spatially adaptable pneumatic environment, which consisted of large air-bags or "bubbles" that inflate and deflate in reaction to visitors. Commercial use of inflatable architecture has remained limited to deployable but unresponsive systems. Some of the explanations for this limited adoption of softer approaches to responsive architecture lie in material reliability, challenges to control systems, and the relatively small number of research groups exploring this space. In recent years there has been a revival in interest in softer architecture that parallels developments in the state of the art of robotics, and material research.

Soft Robotics

The development of Industrial robotics have been historically based on rigid-body dynamics. The focus of control has been on the relationship between motors, loads, and minimising elasticity in linkages to track and position "end effectors" within working spaces. These work spaces are rarely occupied by human presence and up till today, the vast majority of industrial robotics function within highly controlled, humanless environments.

New requirements for robots to work in proximity to human beings and to manipulate more complex objects has encouraged the development of compliant actuation systems that cause no or less damage during inadvertent contact, have superior good shock tolerance, are lighter, exhibit lower inertia, use less power and more accurate and stable in a variety of tasks. Compliant actuators can be found in walking and running robots for example exploiting the natural dynamics such as Denise (Wisse 2004), Flame (Hobbelen et al. 2008), Lucy (Vanderborght et al. 2008), Mowgli (Niiyama et al. 2008), BiMasc (Hurst et al. 2007), Handle etc. Developments in compliant robotics are associated with combination of expertise from very diverse disciplines such as innovative 3D printing, mechanical engineering, microfluidics, biorobotics etc. Numerous new trends and applications have emerged such as Exoskeletons resulting in various launched prototypes - suitX MAX, The Active Pelvis Orthosis, Ekso GT Exoskeleton (Chen and al. 2016), suitX Phoenix Exoskeleton (Leibowitz 2016) and many others. These advances prove promising potential for application as well in architecture and product design related to Human Robot Interaction (HRI), which require close physical contact, and robotic integration into our environments.

Material elasticity is a common characteristic of compliant robotics. Silicone rubbers are being widely explored for the embodied behaviour that can be programmed by careful arrangement of internal air channels. Applications have included soft end effector grippers because of their ability to take the shape of the objects they encounter and their high friction contact. A wide variety of soft elastomeric materials has been tested, in order to optimize their design to achieve required operation space such as soft fluidic actuators consisting of elastomeric matrices with embedded flexible materials (e.g. cloth, paper, fiber, particles). Soft actuators are preferred over rigid actuators when it comes to robotic applications for physical human interaction and delicate object manipulation. Soft robotics utilise pneumatic actuation in combination with morphological design, sensing and control for 'soft bodies composed of soft materials, soft actuators and sensors [that] will be capable of soft movements and soft and safe interaction with humans'(Pfeifer et al. 2012). One of the examples is Cecilia Laschi et al.with their Soft robotic octopus arm (2012) (Laschi et al. 2012). It's worth noting that Mark Fishers and Frei Otto's experimentation resembles some of soft silicon robotics we are seeing appear today. The polymer rubber experiments of Architect Omar Khan installations such as Open Columns (2007), Homeostat (2007), employing the soft kinetics of silicone rubber. These were however passive elastic structures externally actuated by cables. More recently ETH researchers have looked at applications of silicone soft robots with Dino Rossi et al, Adaptive Solar Facade Project (2011) (Rossi et al. 2014). At Interactive Architecture Lab, we have explored a variety of kinetic projects using cast silicone soft robots however the scale issues have limited prototyping to small scale deformable components networked to produce larger surfaces (Glynn et al. 2013). We have moved our Silicone Soft Robotics towards wearable interfaces for haptic interaction such as the Sarotis project (2016) [4], which is an experimental prosthesis that was designed to study whether a person's awareness of space could be amplified using live 3D scanning technologies controlling the inflation and deflation of soft robotic wearable. The applications of soft actuation around the body seem particularly promising but many questions remain about the feasibility of such systems to scale to architectural applications. We are looking to explore actuation of structures between the scale of the body and architecture and have chosen the architectural tradition of the furniture prototype to develop solutions that could lead to larger scale constructions.

METHODOLOGY

Mies van der Rohe said: "A chair is a very difficult object. A skyscraper is almost easier. That is why Chippendale is famous" (Mies quote appeared in Time Magazine, Feb. 18, 1957). Many 20th-century architects like Mies - including Le Corbusier, Marcel Breuer, Alvar Aalto, and Eero Saarinen designed chairs and other furniture pieces that would not only occupy their own buildings but also act as a way of thinking about the intricate details, the formal and material choices that characterised their architecture. For example, comparison between Jürgen Mayer H.'s Lo Glo for Vitra Design Museum brings to mind the Lazika

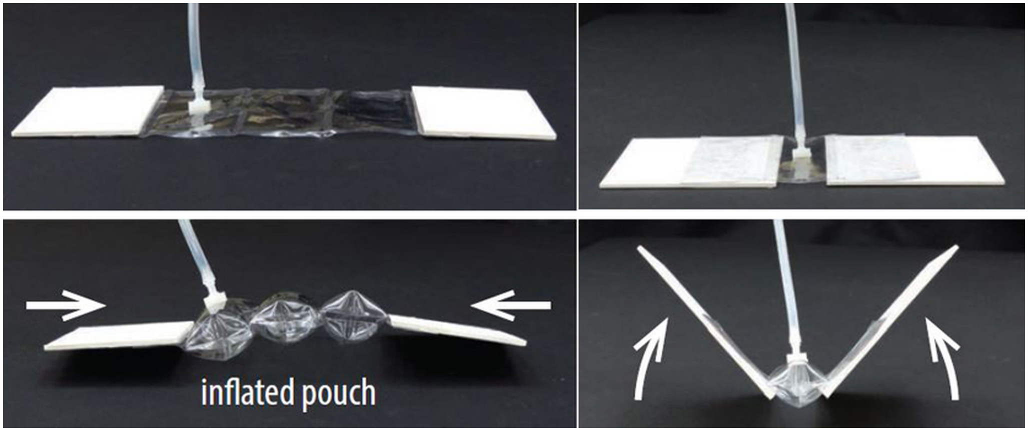

Figure 1
"Pouch Motors: Printable/Inflatable Soft Actuators for Robotics"(Ryuma Niiyama et al. 2014)

Pier he realized in Georgia in 2012. The creation of new furniture is implicit in the development of a new architecture. In 2013 architect Rem Koolhaas unveiled a collection of rotating, sliding and motorised furniture for US furniture brand Knoll. Seeking kinetic solutions not characterised by the rigid dynamics of Koolhaas's approach we initially studied examples of inflatable furniture. Long term durability of inflatable furniture which importantly must maintain air pressure to be stable is a very commonly cited problem leading us to look for structural systems that have stability when deflated and inflated providing a range of stable configurable opportunities. In the field of Meta-Material Research we encountered a fertile research space of rigid and soft material combinations which demonstrate a variety of promising stable configurations that can be actuated by air (Overvelde et al. 2017).

With the ability to reconfigure between several stable states, our interests have moved towards making furniture flexible in terms of several possible functions. We draw on methodologies in metamaterial research that are themselves partly inspired by origami design techniques which provide an ideal platform for the design of reconfigurable systems. In a variety of applications, researchers are looking at transformable molecular structures with embedded actuation potentially harnessing heat exchange, light or chemical energy sources for applications in nano-robotics and "smart" material engineering. Origami principles relating to specific geometries are of particular interest in Molecular Engineering research currently taking place at the Dutch Institute for Atomic and Molecular Physics (AMOLF). Our visit to their labs in April 2017 revealed that alongside the use of advanced mathematical models, paper based origami prototypes remain an essential method of research exploration helping to visualise potential problems and possibilities with geometric configurations. Reconfigurable prismatic structure materials were explored by AMOLF in collaboration with Chuck Hoberman, with the important difference that they are manually controlled and do not seek to solve issues of human proximity that our approach is looking towards nor use soft actuation approaches that would enable more compliant behaviour. We examined two soft actuation techniques.

Pouch Motors

Pouch Motors, were developed exploring printable actuators for enhancing mass-fabrication of robots from sheet materials using easily accessible tools and methods. The pouch motors consist of gas-tight bladders - pouches, fabricated by heat bonding which is an essential part of the fabrication. The theoretical maximum contraction ratio of the linear pouch motor is 36 %. Pouch motors tested in the Lab, were made out of 0.18mm PVC sheet and proved to have 10% contraction ratio, as compared to linear pouch motors made in Robotics Lab, MIT made of 0.102mm PVC sheet, where the measured maximum stroke and tension of the linear pouch motor were up to 28% and 100 N. These pneumatic actuators perform better in case they are fabricated with custom stencils and a heat sealing head for 3-axis CNC machines in order to achieve needed precision for programmable transformations. Nonetheless, for quick experimentation and prototyping manual sealing is simple and does not require expensive hardware. This approach satisfied our aims for an easy and cheap fabrication, and actuation of lightweight structures provided some initially interesting results. However durability was low under loads and pouch motors were found to not scale sufficiently. (see Figures 1 and 2)

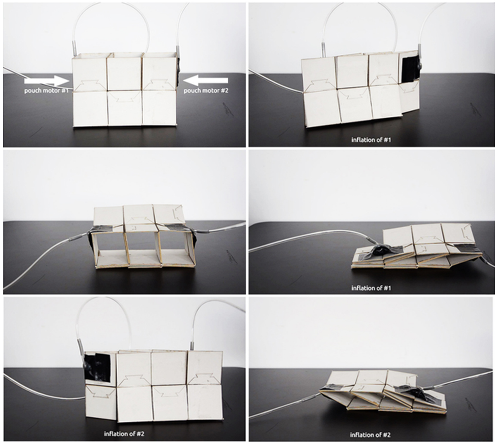

Figure 2
Scaled up hexagonal prism, showing transformation between different states

Air Muscles
Commonly referred to by a variety of terms, such as Pneumatic Artificial Muscles (PAMs), air muscles or McKibben muscles, soft actuators are often made up by an elastic internal bladder surrounded by a braided mesh shell. In case of complex structures which have more rigid states, thus never fold flat, we determined that air muscles are found to work better, being stronger and able to effectively move the structure from one stable state to another. Industrial air muscle actuators are resilient and relatively affordable but at the Interactive Architecture Lab we found in our earlier Golem Project [1] that air muscles sufficiently strong (200N of lift) could be self-fabricated. Our DIY muscles proved to have a contraction ratio of 25% compared to the commercial ones such as Festo's 33% [3].

Mobility: The Roamniture Project
The implicit opportunity of using a robotic technology is that it can become mobile. Our experiments presented below with pouch and air muscles would often appear to exhibit crawling behaviours when actuated so we have embraced this compelling feature for its interaction possibilities with its environment and human users. The first stage of experiments presented below focus on the fundamental mechanics and in doing so we share our design approach which is looking at hybrid soft-rigid dynamics enabled by meta-material principles of bistable and other multistable structures, which we see as advantageous over simply inflatable structures

RESULTS
Our preliminary research has revealed materials-structural compositions that offer promising transformable characteristics with a variety of states of structural stability. Below we share a selection of the most promising. Our prototype's combinations of rigid material and soft actuation provide performance characteristics of soft robotics in terms of compliancy, smooth movement and low inertia, while also demonstrating stability necessary to develop furniture prototypes in our next stage of research. We refrain from too much speculation at this point on the furniture applications but do want to point out some initial thoughts on their use.

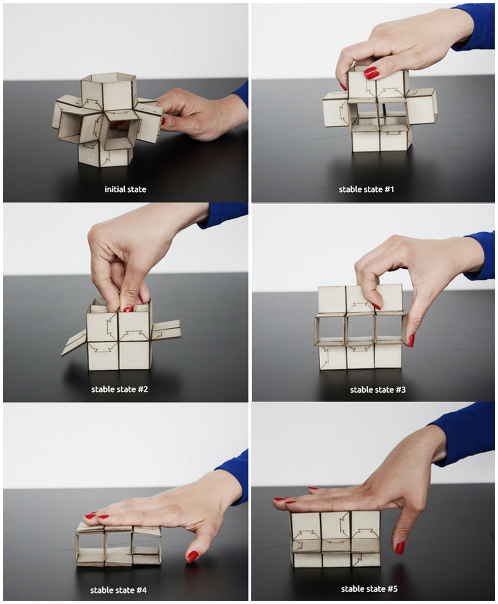

Figure 3
Hexagonal Prism, state variations

Hexagonal Prism

5 stable states (2 primary), the hexagonal base has six rectangular sides. This polyhedron has 8 faces, 18 edges, and 12 vertices. All the edges are uniformly extruded and each extruded unit cell is modelled as a set of rigid faces connected by linear torsional springs, with periodic boundary conditions applied to the vertices located on the boundaries. Degree of freedom of a single unit is 5, while its space-filling tessellation or combination with other units such as triangular prisms, cubes, dodecagonal prisms and others has a lot fewer degrees of freedom, in most cases 2. Moreover, the results indicate that most of the reconfigurable structures are characterized by fewer degrees of freedom than the constituent individual polyhedral. It is found that the mobility of the unit cells is affected by two parameters: the average connectivity of the unit cell, and the average number of modes of the individual polyhedral (Figure 3).

Truncated Octahedron

5 Stable States (Figure 4). A truncated octahedron is constructed from a regular octahedron by the removal of six right square pyramids, one from each point. It has 14 faces (8 regular hexagonal and 6 square), 36 edges, and 24 vertices. In this example, all the edges are uniformly extruded in the direction normal to their faces to construct the extruded unit cell. This results in a 3D structure which has the faces that are rigid and the structure can only fold along the edges, creating a unit that has 5 degrees of freedom, when all 14 faces are extruded. Changing these 5 angles we deform the internal structure and reconfigure the unit cell into many specific shapes. However, when the space tessellation is done, and this unit is combined or multiplied, new space-filling structure becomes completely rigid having a degree of freedom 0.

Figure 4
Truncated Octahedron, state variations

Considering the number of cells truncated octahedron has more potential arrangements when it comes to furniture - working surface / sitting places / space divider / storage spaces. As a divider it can be set to provide more or less privacy, having closed or open cell faces. In terms of lighting it could offer several potential applications where translucency of differently materialized faces could play a significant role. However, materials characterized by higher number of degrees of freedom are characterized by more 'soft' deformation modes. As such, materials with ndof = 1 seem most promising for the design of reconfigurable materials, since they can be reconfigured along a specific direction, while still being able to carry loads in all other directions. This has to be taken into consideration when combining different materials onto a single unit.

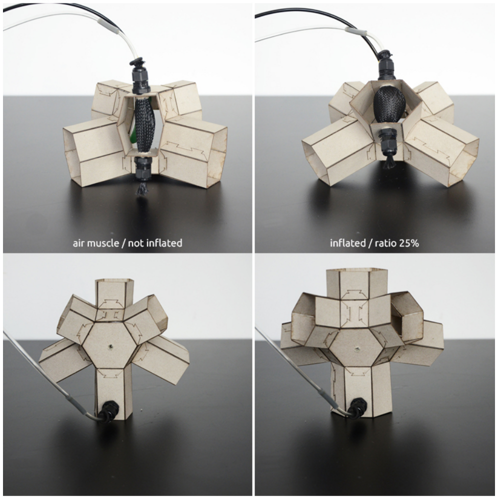

Figure 5
Actuated Tripod (Truncated octahedra modification), air muscle actuation

Actuated Tripod: Truncated octahedra modification

Previously we established that space tessellation of truncated octahedra, when all 14 faces are extruded, becomes rigid having a degree of freedom ndof=0. Shown here, is the example of the individual unit of truncated octahedral, having only 6 extruded faces, while 8 remain rigid. With this principle, both individual unit and a new space tessellation have a degree of freedom ndof=1, in comparison to uniformly extruded previous one where the single unit had 5, but the space tessellation 0 ndof. Three out of six faces went through single extrusion, while the remaining three went through double extrusion. Pneumatic muscles (Figure 5) can raise the height of the structure while remaining perfectly stable, thus giving the idea of variable and adjustable furniture use. Contraction and relaxation of the air muscle (ratio of 25 %) can furthermore achieve certain types of crawling like motion. The movement we got with this test is rather smooth and can be compared to human breathing. In relation to people's proximity of the furniture, such degree of speed is desirable and perceived as pleasant. Possible applications of such a model could range from sitting places towards inclined and adjustable working surfaces with changeable heights (today often introduced for health purposes).

Modified truncated octahedra array

Aforementioned, to further explore the potential of bistability and possible transformation this is the spatial array of 8 tripod units (6 extruded faces / 8 rigid) - modified truncated octahedra, which enhances the reconfigurability of the whole structure having the same degree of freedom as its single unit, ndof=1.
This means that apart from its initial state this structure has only one more stable state. By actuating it we discovered that air muscles (Figure 6) work well with these complex geometrical combinations, however acting different when applied to a single unit tripod than to an array of them, based on the limitations of freedom in their inter connections. Importantly, when it comes to an array, air muscles must be placed equally along the structure in each individual tripod's "leg pockets" in order to uniformly affect the whole unit and remain stable. By placing air muscles, actuated and controlled separately in opposite legs of the tripods, we are able to achieve the movement which causes transformation between the initial to the second stable state.

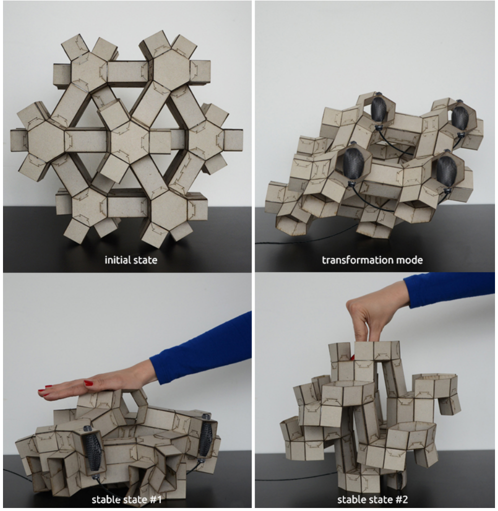

Figure 6
Modified truncated octahedra array, air muscle actuation

DISCUSSION

The inherent behavioural features of soft metamaterial inspired systems provide a range of useful characteristics that lend themselves towards applications in furniture. In addition to compliance with the body, they include self-stabilisation. Our next steps will be to examine control systems that animate these and would allow automated, responsive and mobile behaviours. Body motion planning for control of soft robotic furniture face significant challenges not faced in taking a rigid body approach. Body plans can not be computed with the classical mechanics of chains of rigid and rotational/sliding links. Instead the non-linear complexity of soft dynamic compositions demands alternative approaches. Whereas rigid robotic systems typically employ central control systems, our approach the Roamniture will in its next steps look to the inherent behavioural character of our material compositions and examine light-weight (both material and computationally speaking) systems for controlled motion and behaviour.We intend to address this challenges when we incorporate distributed feedback control into our next prototypes.

As social scientists Herbert Simon pointed out in The Sciences of the Artificial (1969/1996 : 52) "An ant, viewed as a behaving system, is quite simple. The apparent complexity of its behaviour over time is largely a reflection of the complexity of the environment in which it finds itself." This is an understanding all too often overlooked in robot design, and by extension robotic applications to architecture. As the Interactive Architecture Lab is interested in developing robust stimulus-response (behavioural robotics) strategies for system design we see it worth reflecting on even the most primitive of mobile robotic presidents. Grey Walter's "tortoise" robots of the late 1940's demonstrated elegantly that the environment itself is an essential driver of behaviour and that we might consider the modulation of the environment as a method of steering Roamniture rather than thinking only of the internal working states of the machine itself. The next steps of Roamniture will address not only the control systems within the dynamic structures themselves but also their sensitivity to their environment and the potential for the environment to modulate itself in order to control our behavioural furniture.

The remarkably animacy (lifelike quality) of Walter's Tortoises came from their primitive yet continuous and purposeful stimulus-response interaction with their environment. We see this animacy as a positive quality to aspire to and our own air-muscle driven structures through not yet driven by purposeful systems, do exhibit animate qualities by the quality of their breathing motion. The potential for this gestures to exhibit a range of characters is in itself a fascinating unaddressed question latent in work like this. The Interactive Architecture Lab's recent work with puppeteers has taught us that at the centre of communicating all emotional content is Breath. Soft Robotic Furniture has inherently emotive qualities that we intend to study further and take advantage of.

Whether our future steps of research will comprise out of large arrays of small units of geometries or scaling up of current geometries, will be guided by experimentation with larger prototypes planned for the summer of 2017.

CONCLUSION

Our explorative experimentation with actuated metamaterial inspired structures presented in this paper demonstrate a range of encouraging possibilities for new design approaches to soft kinetic architecture. We have identified particular promising geometries that offer a range of shape changing forms and potential functions. By combination of hard and soft components, we imitate the morphology of both hard and soft nature of our own bodies. The next steps for use will be to look to the types of body-inspired stimulus-response control systems that can steer mobile behaviour. In the convergence of techniques from kinetic architecture and robotics our hybrid approach offers a new approach to developing a softer, more intimate, body responsive architecture.

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