Elastic Choreographies

A robotic bending active structure interacting with humans

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This research explores the interaction between an actuated space and its human occupant. The research was carried out using a model consisting of a bending active textile hybrid material system, which leverages architectural elastic robot capabilities and the potentials of soft forms to create artistic performances.

Keywords: *Elastic Robot, Robotic Choreography, Reconfigurable BATH Structure*

Figure 1
Elastic Choreographies performing as an urban canopy

INTRODUCTION

Elastic Choreographies (EC) is a novel robotic elastic system that operates at architectural scale and changes state in response to environmental, human and material parameters. It comprises an aggregation of robotic bending active tensile hybrid (RBATH) units. Global deformations can be achieved by changing the orientation and position of the units' anchor points (Figure 2). EC is part of a larger research agenda on the development elastic robotic structures (ERS) led by Soana, at the intersection of architecture, engineering and robotics.

ERS research aims to develop shape-changing architectural systems exploiting the kinetic potential of elastic structures (Lienhard 2014). Building on a previous framework, EC proposes a novel actuated elastic structure, contributing to the development of methods to design, fabricate and operate ERS. As many researchers such as Lienhard and Schleicher have discussed, elastic systems have significant kinetic potential. Elastic kinetic structures can leverage material behaviours to morph and reconfigure. Compared to conventional rigid body kinematic systems, which require many mechanical parts to achieve a transformation, elastic kinetic structures can achieve large changes of shape using relatively little energy (Schleicher 2016). They are however difficult to design and control, especially at large scale (Soana et al 2020). Their shape is a function of material behaviours, which are particularly difficult to predict for continuously operating systems. Many ERS projects have been developed over the past six years, for example: ELAbot and LOOPS (Soana et al 2020, 2023). Each project was designed based on a different material-actuation principle, application and target behaviour. All share a common conceptual and technical approach. ERS research is based on a re-evaluation of conversations started in the 1960s about adaptive, intelligent environments – from Archigram's visions to Negroponte's "soft architecture machine" (1975). The work questions how current technology can be used to re-evaluate Charles Eastman's conception of adaptive-conditional architecture (Kolarevic, 2009); an autonomous system based on feedback both from spaces and the people using them (Kolarevic 2009). It also builds on Frei Otto's legacy on lightweight systems, taking the integration of material behaviours as a fundamental aspect of architectural design. The ambition of ERS is to continue the legacy of previous work in the field of intelligent robotic structures such as Muscle NSA (Hyperbody 2008), Flexing Room (Kilian 2018) and Felctofin (Knippers et al 2020). It also seeks to integrate approaches used to design lightweight bending active and tensile systems, developed by Frei Otto and others since (Seiichi, Lienhard, CITA, etc.), with robotic solutions that can control global elastic deformations. In EC actuators were strategically placed at the anchor points of the RBATH modules, so that they could trigger large deformations with minimal varyiances in the orientation and position of the module (Figure 3).

EC RBATH units were designed to be aggregated and form a larger architectural system (Figure 1). The system was envisioned as a shape-changing public canopy that could offer multiple experiences, responding to environmental and human parameters.

EC builds on existing ERS existing methods by: 1) extending design and simulation approaches to develop RBATH complex geometries; 2) design and development of a new material-robotic system; and 3) extension of responsive and interactive strategies.

METHODS

EC development was a three-stage ERS process: 1) design of the material-actuation; 2) design, fabrication and operation of the robotic system; and 3) cyber physical control and behaviour.

Design of actuated material system

EC modules comprised a network of RBATH units, with multiple variable-angle and variable-position anchor points that triggered global deformations. RBATH systems needed to be form found as their forms were driven from material behaviour (Seiichi 2020). Due to the difficulty of simulating non-linear material behaviour, numerical simulations of RBATH systems are often validated through physical testing (Lienhard 2014). Module geometrical design was achieved through a multi-state form-finding process using the Kangaroo physics plug-in, Grasshopper (Piker, 2013).

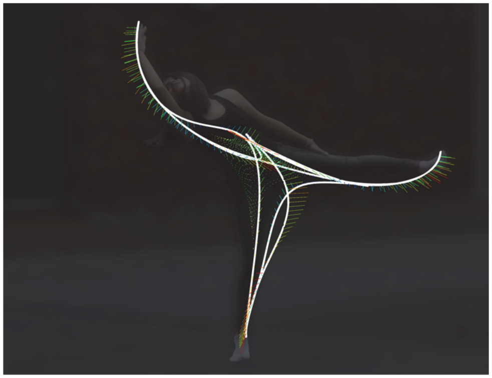


Figure 2
RBATH simulation in Kangaroo and calibration of the material system via K2 engineering

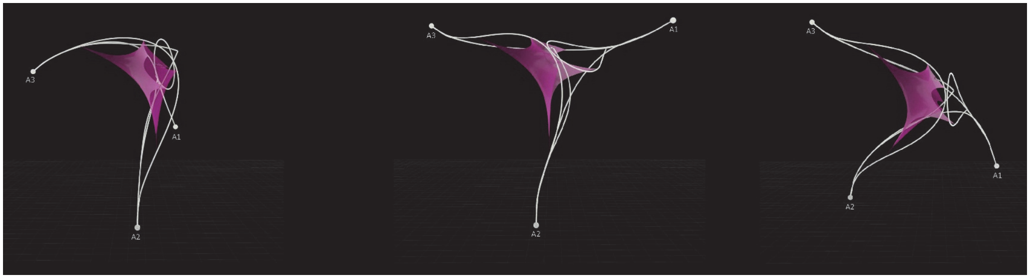


Figure 3
Elastic Choreographies unit changing shape based on angle and position manipulation of its anchor points

The EC design process consisted in the exploration of different RBATH topologies at multiple states. The main design parameters were the number, material, shape and topological rules of the bending active rods and tensile elements.

Each RBATH unit was aggregated in such a way that the anchor points could be connected to an external mechanism that was able to change their orientation and position (Figure 3).

The change of angle or position in the module's anchor points had to be planned carefully in order to maintain structural stability. To enable the change of anchor point position, studies were done integrating a substructure and a custom-mobile robotic arm that could move the anchor points in x,y,z directions (Figure 4). Since the system relied on anchor point movements, the number of anchor points and their position affected the equilibrium of forces and resulting shape. Multiple units were then aggregated into larger systems (Figure 10).

The design of the system at multiple states could be compared to the development of a choreography, as the sequence of actuation determined global behaviours. Many different choreographies of the same module and system of modules could be achieved by varying the order of actuations/operations (Figure 3).

Design, fabrication and operation of the robotic system

The development of the physical robotic system comprises the design and fabrication of the RBATH module and a characterisation and calibration of the system. The RBATH modules comprise a network of carbon fibre rods (CFR) and elastic tensile surfaces (LYCRA) connected to the rods. Two actuation mechanisms were tested: 1) a robotic anchor point that by varying its angle could change rod orientation; 2) an external robotic arm that could move the anchor point position across a substructural grid. Both actuators were built with 3D-printed parts (Figure 4).

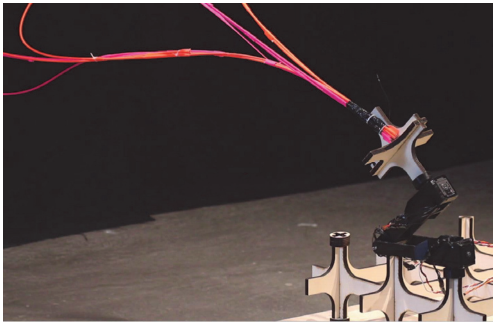
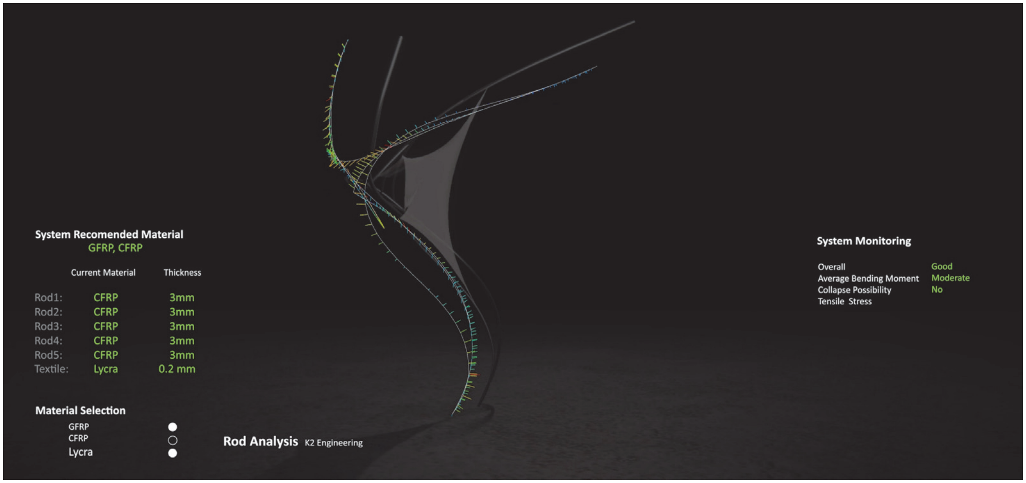


Figure 4
Robotic arm transiting on a 3D grid and manipulating the anchor points of the RBATH model

Both actuation systems employed Dynamixel servos capable of sensing. The control system was built in ROS (robot operating system), writing custom control algorithms in Python3 using the Dynamixel SDK. This was done in order to facilitate the communication and exchange of feedback-control data of the actuators. Once the RBATH units and actuators were fabricated and assembled, a series of calibration and characterisation tests were performed. In this phase, global deformations were observed based on actuation data. These data (such as angle, velocity and position) were stored and collected to inform future system operations.

The initial prototype had a height of 1.5m. It was then upscaled to 3m. The simulation accommodated this change of scale, calibrating so that the final choreographies could emerge from a negotiation between initial design intentions, actual material and mechanical behaviour of the robotic prototype.



System Recomended Material
GFRP, CFRP

	Current Material	Thickness
Rod1:	CFRP	3mm
Rod2:	CFRP	3mm
Rod3:	CFRP	3mm
Rod4:	CFRP	3mm
Rod5:	CFRP	3mm
Textile:	Lycra	0.2 mm

Material Selection
GFRP ●
CFRP ○
Lycra ●

Rod Analysis K2 Engineering

System Monitoring

Overall	Good
Average Bending Moment	Moderate
Collapse Possibility	No
Tensile Stress	

Figure 5
Human responsive behavior : manual User-interface

Cyber-physical behaviour

Once the physical system was calibrated, the final control system was developed in a cyber-physical space, where simulation and robotic data were processed in real time and visualised in a custom user interactive interface. This was possible through a custom pipeline where the simulation in Kangaroo/Grasshopper was communicating to ROS via Unity. Multiple control and responsive approaches were tested, based on: user/designer, autonomous agent and environmental parameters.

Human responsive behaviour

This actuation mode enabled direct control of the EC RBATH unit based on human preferences and movements. A custom interface was developed in Unity to allow visualisation of structural and simulation data and manual control of the physical system. Users could input motor data, receiving sensor feedback and visualising the physical state in simulation (Figure 5).

In the second control mode, human motion was tracked through the Microsoft Kinect sensor. The skeleton was visualised and rebuilt in the Unity engine. Through custom C# algorithms human movements were translated into motor control data, based on the position of the joints in Unity. This enabled the robotic module to change shape based on human motion, without compromising stability and integrity, given that the final behaviour integrated structural and physical feedback (Figure 6).

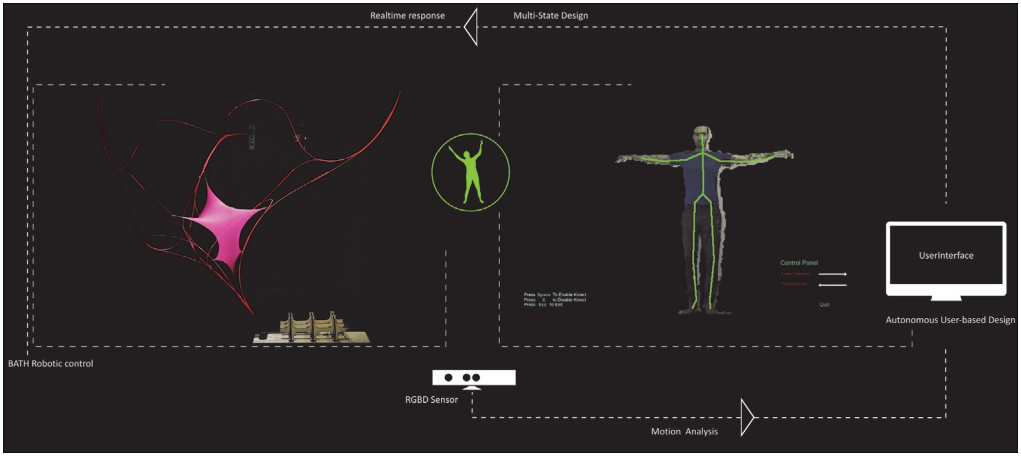


Figure 6
Human responsive behaviour via motion tracking

Autonomous agent behaviour

The second behaviour tested was built as an Agent-Based model (ABM) programmed in C# using the ICD Stuttgart open-source ABM plugin for Rhino/Grasshopper (Long et al 2022). The custom algorithm enabled the researchers to visualise the simulated shape of a selected EC RBATH module, by changing anchor points in a three-dimensional grid, without compromising stability. The aim was to determine rules that enabled the unit to behave autonomously. Within the ABM framework one of the three anchor points of the RBATH module was the active agent. The active agent changed position following an attractor point in a 3D grid. The two anchor points performed as passive agents, where their position was automatically computed to enable structural stability of the module at any time. This was achieved by integrating a feedback loop in the computational system based on all the structural states possible that were considered stable. Displacement of the two passive members was based on a mathematical formulation that continuously checked that the total distance between anchor points remained within a pre-defined range. This ensured that: 1) the average bending moment in elements did not exceed the maximum value (from K2 engineering structural model); 2) the distance between anchor points remained within the stable range (Figure 7). The second rule was set to check the equilibrium of forces in the anchor points. The range came from a calculation of the force reaction of the anchors, calculated in K2 engineering. This enabled the researchers to verify that forces were counterbalanced by structural supports, making them strong enough to maintain global shape.

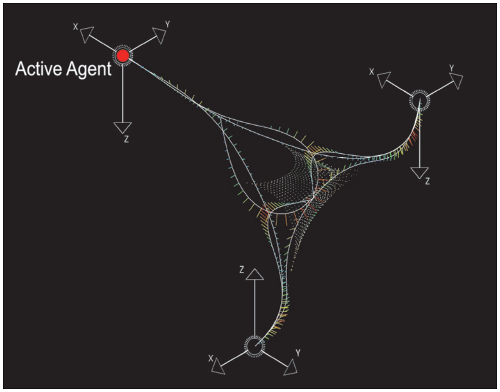


Figure 7
Autonomous behaviour via ABM intelligence

Environment responsive behaviour

The environment responsive behaviour aimed to autonomously generate control data of a given RBATH module to maintain specific shading conditions, based on sun coordinates and occupant moving positions. To maintain a constant shading condition of an occupant, the RBATH model was trained in ML-Agent platform in Unity using reinforcement learning approaches. The system computed the orientation of anchor points to allow for global deformations, thus providing both shadow and enough volume between its occupant and the canopy structure (Figure 8).

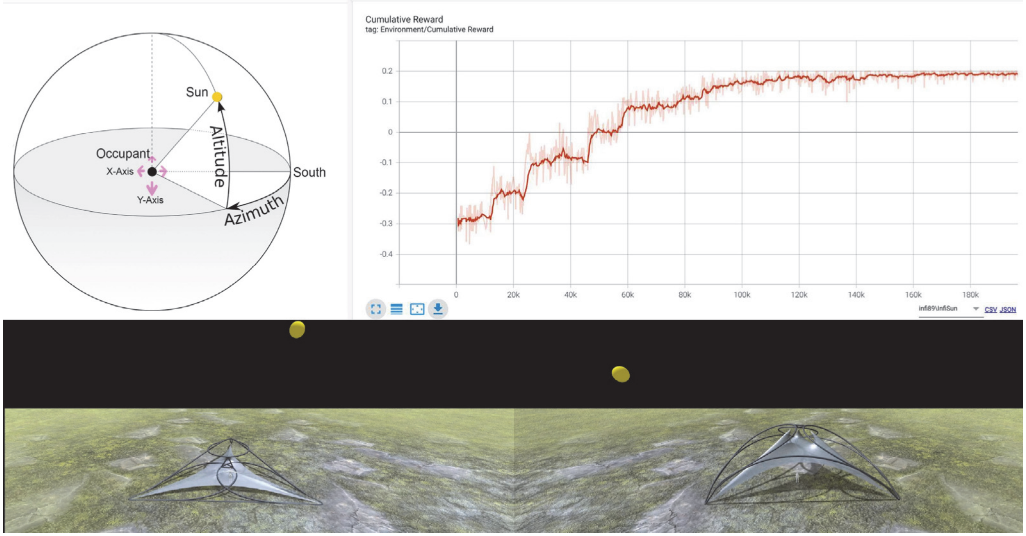


Figure 8
Environment responsive behaviour via reinforced machine learning ; Top left: training parameters; Top-right: training progress graph; Bottom-left: model failure before training; Bottom-right: trained model

The machine learning process was based on a feedback data exchange between ML-Agent inside Unity 3D and Kangaroo Rhino/Grasshopper. Elastic robotic agents were trained using a reward system, to minimise agent failures. The training workflows were conducted via a real-time data exchange between Unity and Grasshopper. In each learning episode, random input data were transferred from Unity to the Kangaroo as numbers responsible for the orientation of the anchors. The resultant geometry was sent back to Unity to evaluate the agent's performance. Geometry was evaluated based on the training logic in a reward-based system. Training logic was based on observation of the two effective parameters: 1) the sun position; and 2) the occupant's position in the training area.

In each trial episode, the agent examined if the sun's rays hit the human body or not. It also checked that there was sufficient space available for the human. A 3D ray represented the sun's rays; a sphere represented the minimum space required around the human body. If the ray collides with the occupant, the training episode ends and the agent receives a negative reward for failing to provide shadow for the occupant. If the ray does not collide with the human body but the sphere collides with the agent, the agent receives a low amount of negative award, for failing to provide sufficient space for the occupant. If neither of the negative conditions occur, the agent was successful in providing shadow and space, and the agent receives a positive reward. By testing more values, the agent response became more reliable, and the outcome of training led to an autonomous trained agent that could react to different sun and moving occupant scenarios in the trial environment.

RESULTS

Through the development of previous methods it was possible to produce a series of architectural structures and functioning robotic systems. In the digital design space, we proposed multiple large canopy urban structures (Figure 9). The approach was based on the design process articulated above, with robotic RBATH units and aggregations generated to achieve specific design goals. The overarching ambition was to generate different spatial experiences achieved with minimum actuation via positioning anchor points through a mobile robotic arm.


Figure 9
EC actioning as intelligent urban canopies

The initial studies focus on the basic EC unit in a custom designed user interface, where the user/designer could select basic design objectives including site and typology. Various actuation and choreographies could be produced and analysed. The design process of the unit could be manual or autonomous. In the manual mode, the user could act as choreographer and compute control data of the anchor points to design a choreography out of the predefined library. In the autonomous design mode, the system relied on ABM for design and reconfiguration; once a site has been selected by the user, the robot begins to morph based on the predefined choreographies.

The final studies focused on exploring multiple EC units which could form a large-scale architectural form that hosts humans (Figure 10).

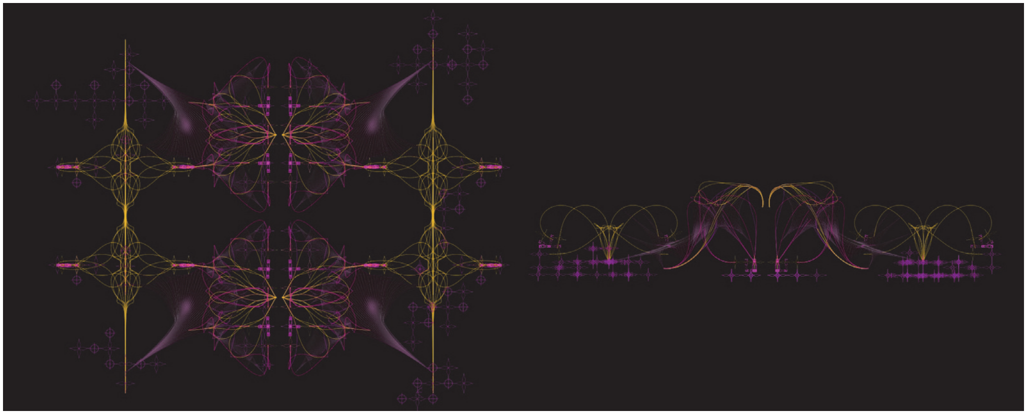


Figure 10
EC large model (left); timelapse plan (right); timelapse elevation

Alongside the digital studies, several fully operational robotic prototypes were tested. These prototypes shared actuation principles (anchor point manipulation), but used a different number of actuators and different typologies.

Taking two prototypes for discussion here – The first focused on performing choreographies in response to the motion-tracked human. The robot manipulated the RBATH model to respond to the counterpart human dancer (Figure 11).

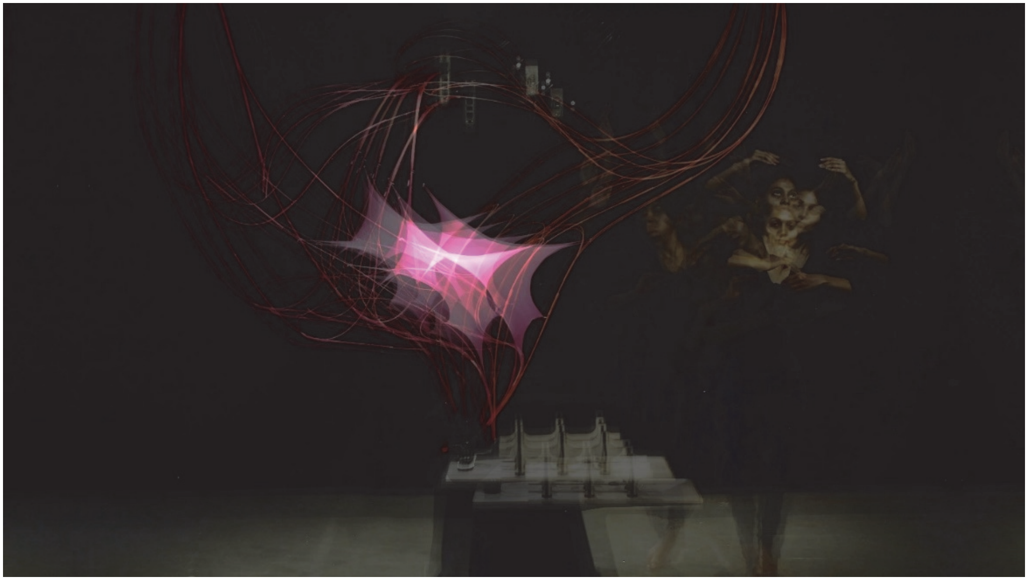


Figure 11
Human-machine interaction; EC dance with human counterpart

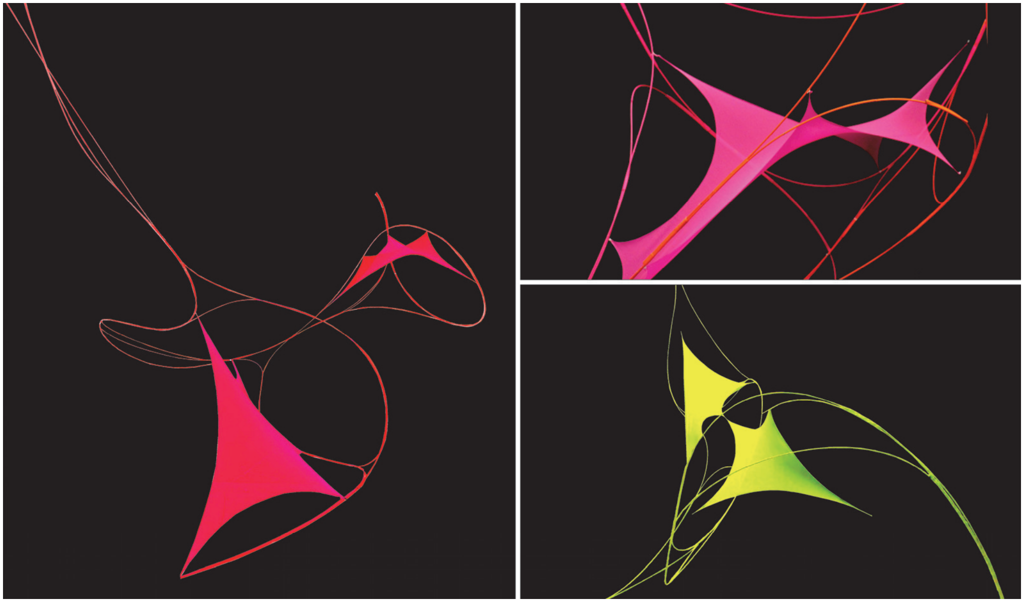
The second was a portable custom model on a human scale that was developed for rapid setup in the outdoor environment (Figure 12). Its anchor points were engineered for modular assembly as part of the House Block Exhibition in London (Figure 12). Another module was built in an external environment and performed (Figure 12).

DISCUSSION AND OUTLOOK

Testing multiple prototypes has demonstrated that the balance of flexibility and stability of the system is an important parameter to make the system remain lightweight and deformable to change shape with minimum actuation. This balance was achieved in each test through the use of different material strengths, textile shapes, and positions of attachments in bending elements.

Development of the application platform marks an initial attempt to speculate on the future of robotic architectural modules that can perform artistic choreographies. Several complex parameters need to be considered due to the complexity of the real-world conditions, especially in outdoor environments where the system's lightweight will be challenged by unpredictable forces such as wind and precipitation.

Figure 12
EC physical prototype (left); House block Exhibition (right-top); portable model at human scale (right-bottom); outdoor model at human scale (left-bottom)



On the other hand, the relationship between music and dance choreographies highlights the EC's hearing ability. In the next step, the EC performer requires the integration of audio sensors in the robotic model and the data flow of the computational platform. In addition to technical upgrades, future work will focus on the development of AI (Artificial Intelligence) processing systems in order to plug more complex behaviours into the cyber-physical model. Autonomous behaviour will be upgraded to respond to more environmental factors such as weather and light.

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