Prototyping Adaptive Architecture

Balancing Flexibility of Folding Patterns and Adaptability of Micro-Kinetic Movements

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The design process of dynamic architecture has been an emerging topic in recent studies, in which researchers try to find an effective method of generating and controlling adaptive components. In this paper, we present a digital-physical modelling process that seeks to explore tectonic fusion of origami folding patterns and micro-kinetic movements. A flexible modular prototype system is developed and evaluated through combining origami-based fabrication simulation and mathematical characterisation mimicking the pinecone's nastic movements. The modular design system is then applied to an urban site as a test case study. The results show how the pinecone-like nastic movements may be translated into design and fabrication of an adaptive architecture. We discuss the lessons learned from the digital-physical prototyping process finding the balance between geometric flexibility and micro-kinetic adaptability.

Keywords: *adaptive architecture, origami folding patterns, micro-kinetic movements, pinecone, parametric modelling, digital-physical prototyping*

RESEARCH CONTEXT: ARCHITECTURAL ADAPTABILITY AND FLEXIBILITY

The development of digital applications has informed a new understanding of architecture design, in which building structures and building elements are no longer permanent, fixed or immobile (Schumacher, 2010). As dynamic architecture becomes more popular and applicable, there have been immerging questions about its purpose and effectivity. One of its typical employments is to respond to changing functional and environmental requirements. Although this viewpoint has potentials in creating more sustainable and fascinating architecture, it requires careful researches and suitable strategies during the design process, to achieve meaningful mobility and efficient controlling mechanism (Megahed, 2017).

This study proposes a design process that can be suitable to prototyping adaptive architecture. Developed from a dynamic component design, the process explores the balance between architectural adaptability and flexibility. While an architectural compo-

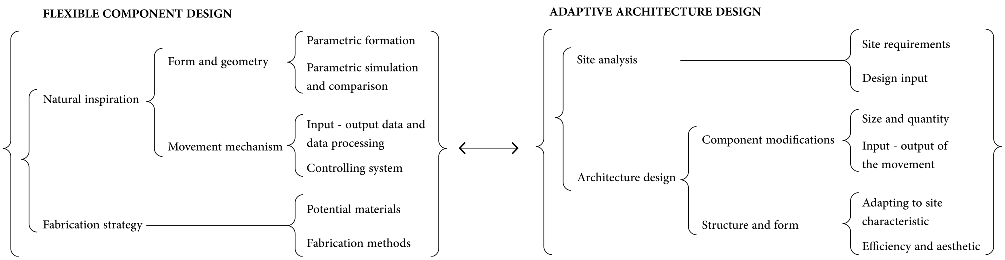


Figure 1
Adaptability and flexibility

nent needs to be flexible to be applicable to different environmental and functional requirements, the adaption process applied to a specific site transforms it and limits its flexibility. Therefore, the parametric tools were used in both ways: to generate the flexibility as well as to limit it to gain adaptability. In other words, the design process becomes an information feedback loop between idea development and (site-specific) possibility evaluation (Figure 1).

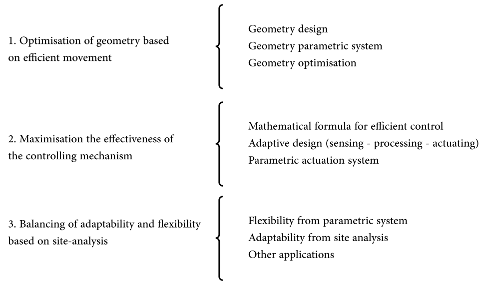


Figure 2
The design process

The concept of optimising architectural components to gain maximum effectiveness in this paper is derived from the inspiration of "morphogenesis". As a term used in natural sciences, this process continuously evaluates geometrical forms until they reach a goal of adaptation to a specific environment or a known requirement (Roudavski, 2009). To reduce the generating time and resources, a hypothesis is proposed, in which the architectural optimisation process needs to be limited by sets of rules based on phasic goals, in order to gain efficiency. Following this rule, the design process is proceeded in three phases: (1) Optimisation of geometry based on efficient movement; (2) Maximisation the effectiveness of the controlling mechanism, and (3) Balancing of adaptability and flexibility based on site-analysis (Figure 2).

PINECONE NASTIC MOVEMENT: AN INTEREST IN BIOMIMICRY

As living organisms, plants are strongly dependent on their surrounding environment, because of their limitation in mobility. Therefore, the ability of adaptation to environmental conditions becomes one of the most important factors affecting their survival rate (Darwin 1880). Since there are similarities of passive adaptation between plants and architecture, many studies have considered this phenomenon and tried to find their applications in architectural design (Hugh 2004). However, there is one spectacular vegetative reaction which could be better modelled as a source of inspiration in the making of digital interactive architecture: nastic movement.

This reaction is defined as the movement of plant parts, which is caused by an external stimulus but unaffected in its direction (Braam 2004). In this study, we investigate the mechanism of pinecone nastic movement as a reference model to design a kinetic architectural system which can interact with its surrounding. To maximize the survival rate of its descendants, the pine tree developed a structure to safely protect and distribute its seeds, which is the pinecone (Harlow 1964). This structure contains different arrangements of fibre which reacts differently to environmental condition, thus makes sure that the pinecone only opens and spreads its seed in the suitable warm and dried weather (Dawson 1997) (Figure 3).

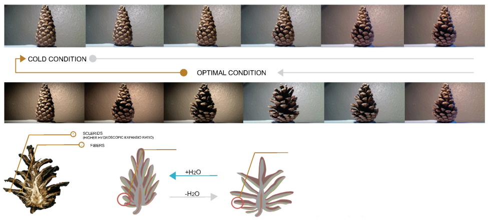


Figure 3
Pinecone natural structure and mechanism

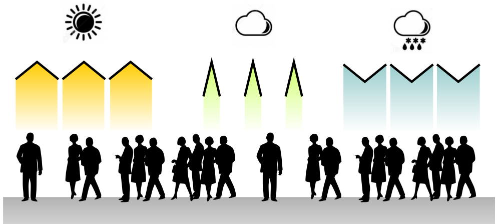


Figure 4
Multi-function component

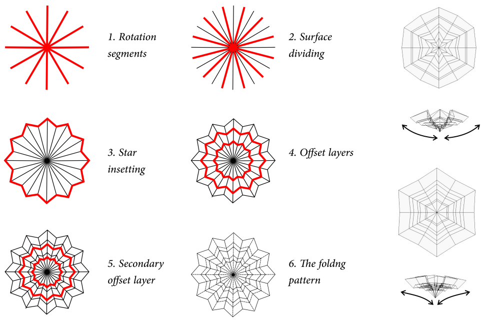


Figure 5
The ANO (Alex-Nonn) origami folding pattern development

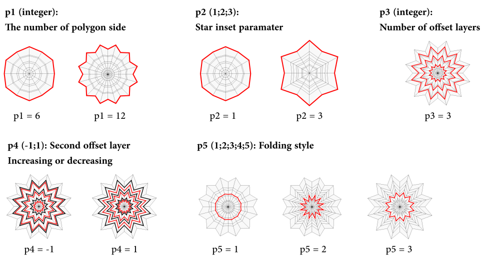


Figure 6
Parameter explanation

The mechanism of pinecone scale movement is complex, involving different materials at a micro scale, which has been studied and applied into material science (Reichert 2014). However, in this study we proposed a simple parametric model that provide a mechanical-based bio-mimicry in the form of a kinetic architectural system, taking in the same inputs (environmental conditions such as temperature, humidity) and giving out a similar output (the movement of open and close). This component is expected to be applicable to different sheltering structure, such as pavilion, canopy and building façade; with multiple functions based on its mobile ability, i.e., sun shading, light filtering, water collecting (Figure 4).

ORIGAMI FOLDING PATTERN GENERATION AND OPTIMISATION

Origami is the art of creating three-dimensional geometry from two-dimensional planar surfaces (Megahed, 2017). Originally developed in Japan, this process of folding allows the geometry to transform itself, generating endless forms and spatial properties (Peraza-Hernandez et al. 2014). As a result, many researches have looked into the mechanism of mathematical calculating, generating and controlling origami patterns (Fei and Sujan, 2013). On the other hand, origami has long been studied and applied in architecture science as folded structures (Megahed, 2017). The raising awareness of sustainability has created a trend of using recyclable materials such as paper in the construction industry (Wu, 2015). Explorations by Shigeru Ban through technical tests suggested that paper-based product, i.e., cardboard, can be a choice for real-scale architecture (Ban et al., 2009). Therefore, origami pattern, indeed, has the potential to be applied in transformable, adaptive architecture since it satisfies the demands of light, flexible, self-supporting structures that have kinetic behaviour.

This study proposes a new origami pattern, named as ANO (Alex-Nonn), which is a radially symmetric geometry and based on the basic rotation pattern. The generation process involves five steps, as

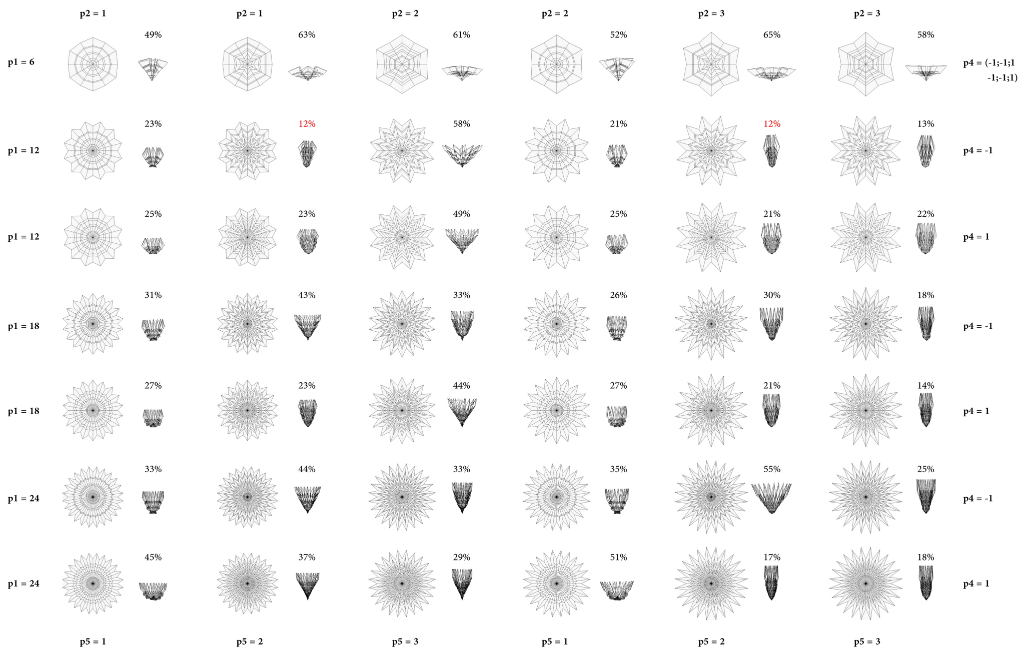


Figure 7
ANO pattern parametric generation and evaluation

shown in Figure 5. While the star inset helps the closing and opening behaviour more efficient, two offset layers provide an attractive curvature outline and more elastic characteristic for the geometry. Overall, the purpose of using the ANO pattern is to interconnect all structural elements in one folded surface, which is more efficient in term of controlling the movement. Benefits from this design include: (1) Lightweight material and less structural elements required; (2) Efficient controlling method due to homogeneous movement; (3) Providing aesthetic and attractive architectural shape; (4) Continuous sheltering area.

Based on mentioned rules, there are a large quantity of ANO patterns that can be generated, yet they do not share the same behaviour when folding. To choose the most efficient pattern in term of efficient controlling, a parametric system is developed. There are five input values (p1 to p5) used to modify the shape and complexity of the planar pattern (Figure 6). 42 generated patterns are then virtually folded by kangaroo at the same folding angle (5π/6) and then compared based on their F% value, or folded size percentage (the width after folding / the flatten width %) (Figure 7).

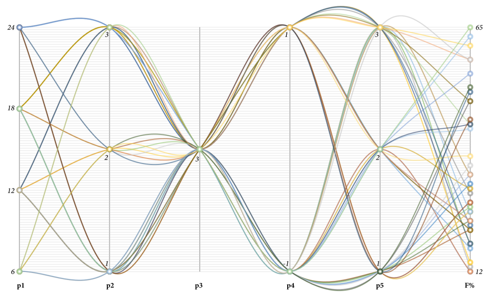


Figure 8
Data analysis of the ANO pattern's parametric generation system

The result of this calculation is then integrated

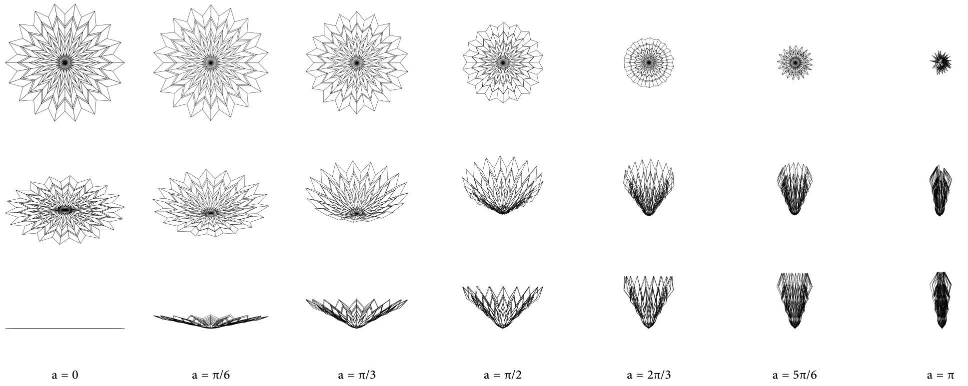


Figure 9
The chosen ANO pattern's detailed parameters and behaviour.

in a Python data analysis and visualisation algorithm for future use (Figure 8). Eventually, the pattern with the smallest F% value (12%) is chosen, since it has (1) more efficient behaviour for controlling, (2) faster movement, and (3) less material and energy required. Its detailed parameters and folding behaviour is shown in Figure 9.

DEVELOPMENT OF THE MATHEMATICAL FORMULA FOR CONTROLLING MECHANISM

Since the ANO pattern is a radially symmetric geometry, it can be simplified into one planar movement system of lines and points. The open-and-close behaviour is then driven by a single-directional control point moving along the vertical centre axis. This system is shown in Figure 10, in which 'a' is the simplified ANO panel, 'L' is the controlling structure, and 'M' is the movement point. Since the design goal is to create a multi-functional component, the panel is expected to rotate in the range of 180 degrees, allowing it to flexibly flip to either directions. This movement behaviour requires some mathematical criteria, including: -90 ≤ α ≤ 90; L > a; and a > 0. To translate the rotation angle (α) to linear movement (M), we developed a mathematical formula, whose inputs include the angle α and structural lengths: L, a; and output is the value of OM (Figure 11). The movement is divided into two phases, in which α ≥ 0 and α ≤ 0.

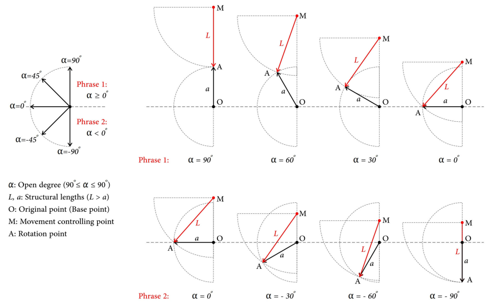


Figure 10
Simplified behaviour of the controlling mechanism

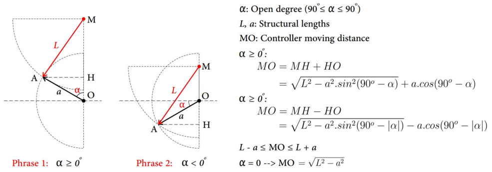


Figure 11
The mathematical formula for controlling mechanism

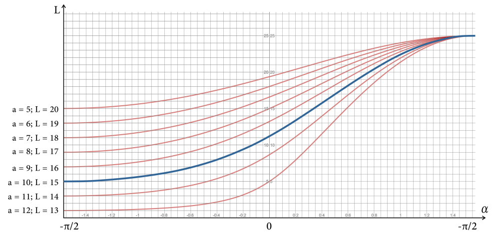


Figure 12
Comparison of different L-a pairs

To maximise the controlling effectiveness, different values of L and a, with L + a = 25, are compared, in term of (1) the range of movement, or the efficiency; and (2) the accuracy of movement. The mathematical graphs in Figure 12 show that while some L-a pairs generated big ranges of OM values, which is not efficient, others have graphs coming too close to 0, which is hard to achieve the accuracy. Eventually, the pair a = 10 and L = 15 is chosen, as its mathematical graph has a neutral behaviour.

By implementing this mathematical formula and the ANO pattern in Rhino-Grasshopper environment, a parametric system was created (Figure 13). This system can generate potentially an infinitive number of architectural structures employing the same mechanism, thus maximise the flexibility.

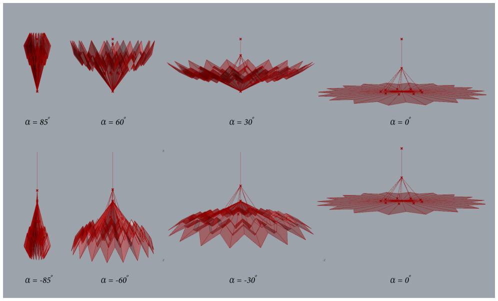


Figure 13
An ANO pattern and controlling mechanism generated by the parametric system

ADAPTIVE DESIGN: SENSING, PROCESSING AND ACTUATING

To develop the automation of the component, a combining workflow of virtual and physical prototyping is proposed, using Grasshopper and Arduino coding (Figure 14). Environmental data is collected by using the DHT11 Temperature and Humidity Sensor, then stored into CSV files and visualised by the Firefly plugins of Grasshopper. Those data are then remapped to the movement angle α, which determines the behaviour of the component. Synthetically, if the humidity is high, the component will act like a water collecting device ($0 \le \alpha \le 90$), and if the humidity is low and the temperature is high (hot), it will then be a shading device ($0 \ge \alpha \ge -90$).

The mathematical formula is then used to calculate the coordinate location of controlling point M. Based on previous location, a movement distance to reach the new destination is determined, which can be either positive value (move up) or negative value (move down). With specific structural sizes (L and a), this workflow is a linear process, which allows the component's behaviour to be easily controlled. To test the workflow, an actuated model is built, using a threaded bipolar motor. Two additional components are added: (1) The physical structure system (Figure 15), and (2) The translation between movement distance and the number of motor's steps.

On the other hand, we also developed a virtual simulation algorithm in Grasshopper to study the group behaviour of multiple components, which is not possible to do in physical prototyping. One component is chosen as the Driver, which will be the first one to receive the movement signal. Others will follow this Driver, or in other words, have delays in their signals (Figure 16). In order to do that, the initial angle α is calculated into a list of decreasing (if $\alpha \ge 0$) or increasing (if $\alpha \le 0$) values. This mechanism suggests further application of these components when they are installed multiply on shelter surfaces, which is not only to provide the usability of shading or protecting, but also to generate joyful experience as an installation for people inside and outside its space to enjoy.

ADAPTING THE PROTOTYPE TO AN URBAN SITE

To fulfil the architectural design process, the component is then put into a real site. The idea here is twofold: (1) to test the flexibility of the structure if it can adapt to different topographical requirements, and (2) to preserve its kinetic characteristics through an interactive installation at upper layer. The chosen site is an old canal basin in Sheffield, England called Victoria Quays. The basin was a cargo port in late 20th century, which is now transformed into a site of business and leisure spaces. With notable quantity

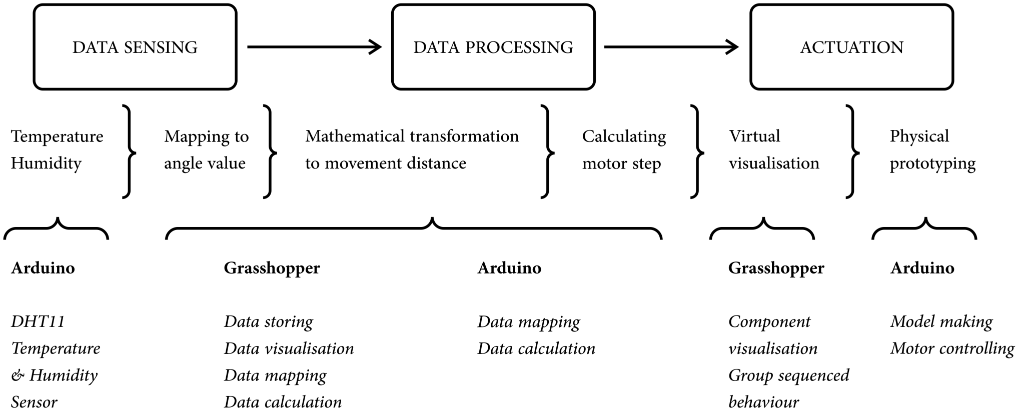


Figure 14
The adaptive
design workflow

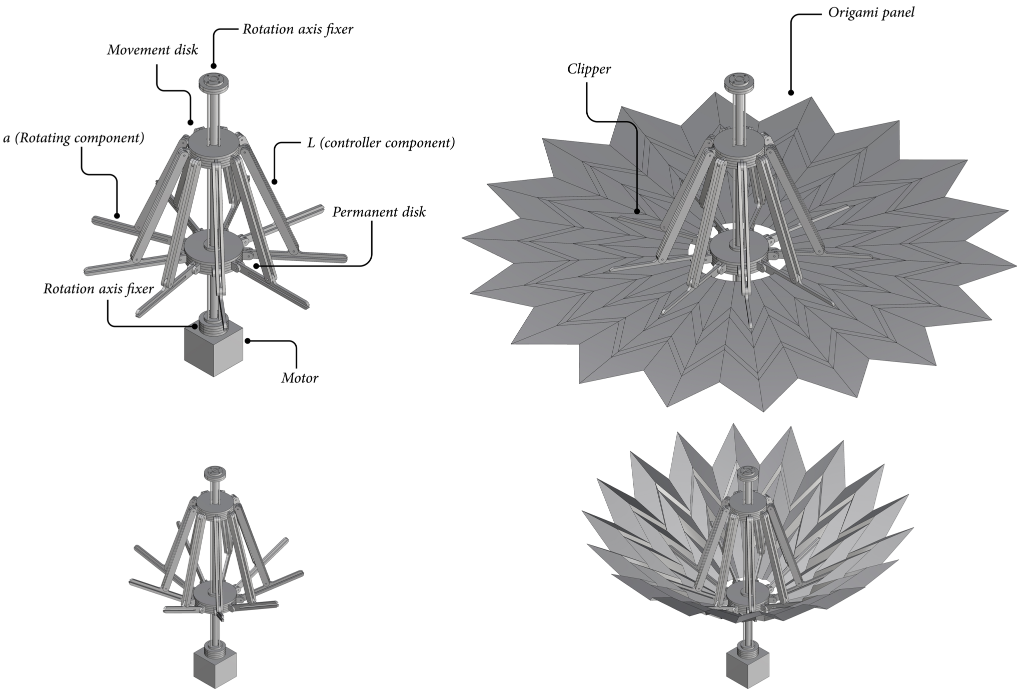


Figure 15
The model
structural system

Site characteristic	Design requirements	Design inputs
Site for outdoor activities on land and on water with canal boats	Servicing human activities on multiple environmental context	A pavilion haft on land and half on water
Dynamic behaviour of tidal river	Adapting to different water levels	Movable pavilion structure
Site for leisure activities	Providing playful experience	Possibilities of interacting with users
Lack of outdoor shelter and shaded spaces	Adapting to weather conditions	Dynamic architectural movement adapting to weather data

Table 1
Site analysis and design inputs

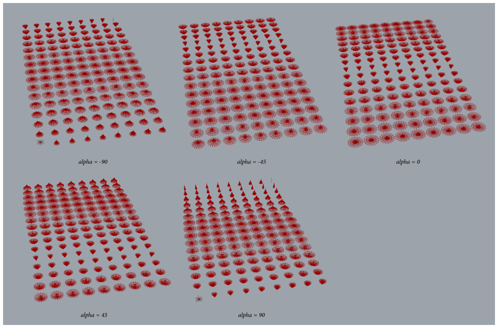


Figure 16
Group behaviour of multiple panels (while α = 45, α = 90)

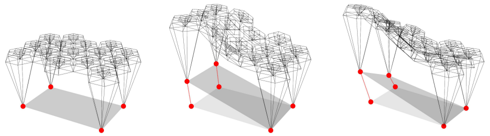


Figure 17
Testing the adaptability of the pavilion on different water level

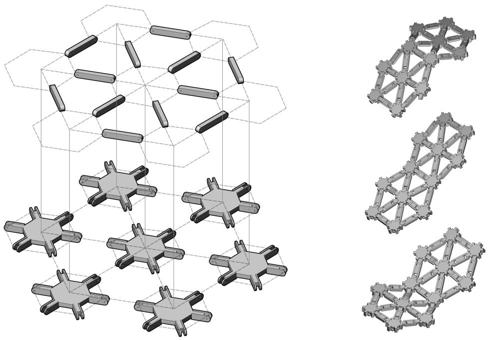


Figure 18
Structure behaviour of the super-structure layer

of tourists and citizens going to the location daily, the proposal is a dynamic pavilion used for semi-outdoor activities and is also expected to be a new tourist attraction. The site's characteristics and how they are transferred into design inputs are shown in Table 1.

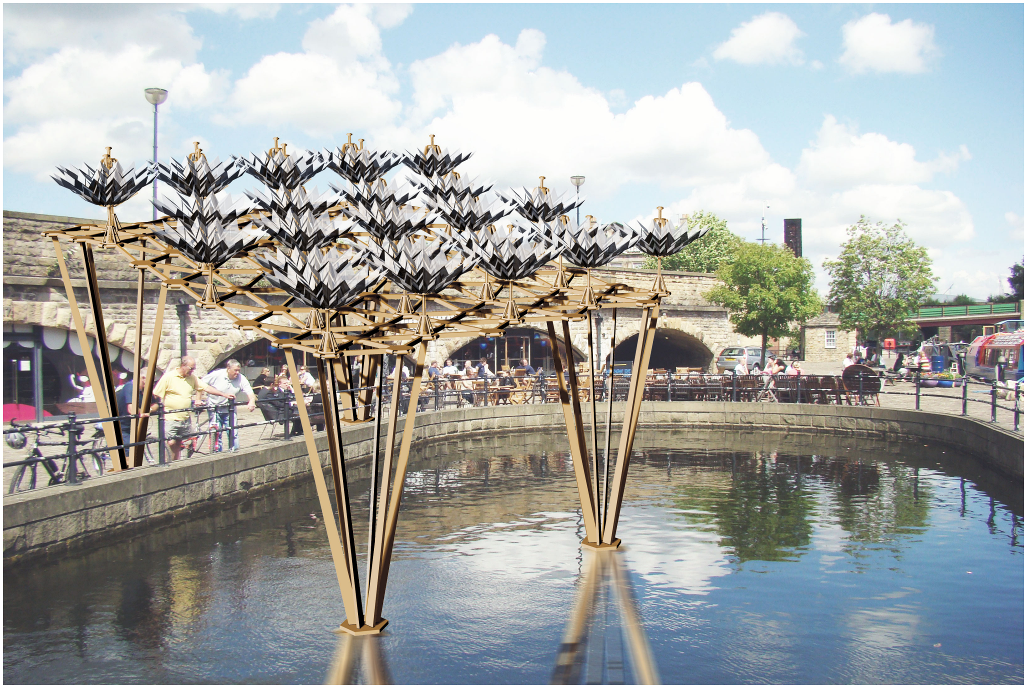
A hexagonal grid structure is chosen due to its compressive and tensile strength also its resemblance to the cell system (Her 1995). To test the structure's adaptability, a parametric function using Grasshopper and Kangaroo is introduced to simulate different topographical conditions, which is, in this case study, the changing datum of each column base as presented by the water level (Figure 17). Specific input values such as the number of cells, the limit of cells' deformation and the maximum rotation angle between each cell edge is also used in the test function. A structural system is then developed for this super-structure layer, fulfilling the requirement of adaptability (Figure 18). Meanwhile, the upper layer of the pavilion is a group of ANO components, which can be interactive to users and the contextual environment.

CONCLUSION AND FURTHER DEVELOPMENT

The study proposed a new design process that started from architectural flexibility and developed the adaptation to the specific contextual conditions. Since kinetic architecture requires complex engineering task and integration of different disciplinary (Megahed, 2017), this design process allows a mobile component to be applied in different conditions and requirements. While parametric function provides dynamic flexibility to the structural form and function, contextual characteristic limits its possibilities and increase adaptability.

New findings of this study include: (1) The design process of an architectural origami pattern, which has an optimisation framework that can be applied to other patterns; (2) The adaptive architecture design workflow, which proposes the effectiveness of using mathematical formula in movement control, and the usefulness of parametric system in structural generation; (3) The combination of virtual and physical prototyping in simulating and processing architectural actuation, in which individual and group behaviour can be implemented together. On the other hand, the study also introduces the new ANO pattern and component, with the ability to be applied on diverse shelter surfaces, i.e., pavilions, canopy, building

Figure 19
Visualisation of the whole pavilion on the chosen site



façade (Figure 20).

To extend the scope of the design process, we will further address user-driven elements to the movement controlling system. This step can be considered as a development to increase the architecture's adaptability. Application of different sensing system is proposed to collect input data, i.e., human movement, sound, light, ..., which then will be implemented into the mathematical calculation process. A user-interactive behaviour system is also expected to be integrated into the design, to provide playful activities to the chosen site.

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Figure 20
Application of the ANO component onto a hypothetic building façade.

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