Interactive Skins for Architectural Adaptation: Design and fabrication of a dynamic electro-mechanical unit

Youness Yousefi[1], Vera Parlac[2]

[1] University of Calgary, Calgary, Canada
youness.yousefi@ucalgary.ca
[2] New Jersey Institute of Technology, Newark, USA
parlac@njit.edu

Abstract. Interactive architecture is a concept that focuses on self-governing behaviour through engagements with the environment and users. This paper introduces designing and fabricating a responsive building skin made of several small unit cells, replacing centralized and hierarchical architectural systems with open and extensible distributed networks. The proposed concept involves modular structures with adaptable building components, allowing greater flexibility, self-government, and resilience than centralized systems. A cone-shaped hexagonal electro-mechanical unit functions as a three-dimensional aperture, opening and closing mechanically using custom-made linear actuators. The aggregation of units forms a dynamic surface that can be installed inside, outside, or on both sides of a transparent wall. The interactivity of the aggregated system was simulated and calibrated using the grasshopper parametric virtual modelling plugin for Rhinoceros. A prototype of five modules was constructed and tested for thirty days, revealing the highest susceptibility to damage in the components.

Keywords: Interactive architecture, Three-dimensional aperture, Modular design, Linear actuator, prototyping.

1 Introduction

Buildings often undergo change during their use and are regularly renovated or remodelled. The capacity to change allows architecture to respond and adjust to the evolving needs of its users (Jaskiewicz, 2013). These changes often address the reconfiguration of spaces within the building. However, the need to more effectively respond to the changing climate and environmental conditions has placed a special emphasis on the building skin and its capacity to mediate or adapt to these changes. Due to low energy efficiency and excessive energy consumption, buildings globally consume over 30% of total energy (Abergel et al., 2017).

Introducing kinetic elements in the design of a building envelope has the capacity to address this problem effectively. They offer flexibility, adaptability, transformability, and interactivity (Kronenburg, 2007). Integrating mechanically moving parts, sensors, and actuators controlled by a central system enables buildings to respond to weather conditions and optimize their configurations.

However, there are two challenges when it comes to the integration of kinetics into a building envelope. Firstly, these systems often do not integrate seamlessly with the traditional building envelope and are often add-on installations to conventional designs. Secondly, the embedded systems' linearity restricts the adaptability of automated buildings to unforeseen conditions. While building automation provides flexibility and responsiveness, it typically operates based on pre-determined actions predicted by designers, limiting its overall adaptability (Jaskiewicz, 2013).

This paper introduces the design and fabrication of a responsive building skin made of modular small unit cells. We propose replacing centralized and hierarchical architectural systems with open and extensible distributed networks. The concept proposes modular structures comprised of numerous adaptable building components, granting them greater flexibility, self-government, and resilience than a centralized architectural system. The adaptation mechanism in this kinetic system relies on developing and maintaining interactions between units and the building inhabitants and among units themselves.

1.1 Background

The idea that buildings should respond to the dynamics of their environment originated in the cultural and technological shift in the early 20th century. Architects like Antonio Sant'Elia, an Italian futurist, imagined buildings that were oriented towards the circulatory and transportation networks of the city, acknowledging their transformational power (William et al., 2006). Le Corbusier popularized the concept of a house as a machine for living (Corbusier, 1923). The emergence of more progressive views on responsive architecture in the mid-20th century was strongly influenced by the science of cybernetics that focused on the relationship and feedback between an object and its environment (Rosenblueth et al., 1943). British Cybernetician Gordon Pask (1969) introduced cybernetic theories to architecture, emphasizing the potential for buildings to interact autonomously with their users. He considered buildings as dynamic functional systems that engage with human society through interactive environments, leading to knowledge creation (Pask, 1976). John Frazer, British architectural academic (1995), expanded on the systemic aspect of self-conscious architectural spaces, exploring computation strategies such as neural networks and genetic algorithms to enhance the embedded intelligence of these self-reconfiguring models.

The emergence of ubiquitous computing has caused technology to become less noticeable in our lives (Krumm, 2010). A new physical world has formed that is characterized by hidden sensors, actuators, displays, and computational elements. These technological components seamlessly blend into everyday objects and are connected through a continuous network (Weiser et al., 1999). This concept has led to the development of the Internet of Things (IoT), which involves a network of interconnected objects ranging from books to cars and household appliances. These objects are embedded in complex systems, have dedicated Internet Protocol addresses, and use sensors to gather information from their surroundings. They also utilize actuators to interact with the environment, such as air conditioning units that adjust based on the presence of people (Atzori et al., 2010; Smeenk & Petock, 2023; Vermesan & Bacquet, 2018). However, despite the rapid advancements in information technologies, mainstream architecture has not fully embraced cybernetic concepts or the innovations of ubiquitous computing. Instead, these systems are often added to existing buildings and have limited functionality in terms of communication, control, lighting, and environmental aspects and have not been integrated into the spatial organization of the environment (Aldrich, 2003).

Today, when discussing interactive architecture, we will encounter terms such as smart, performative, participatory, immediate, kinetic, and sustainable architecture. They all seek to create a common ground for enhancing the reciprocal relationship between users and the built environment.

1.2 Interactive Architecture

Interactive Architecture (IA) refers to buildings and spaces communicating actively with users and surroundings. According to Pask's (1976) conversation theory and Haque's (2006) insights, dialogue is crucial in IA, allowing occupants to shape their spaces by exchanging information and building new possibilities. Achten (2019) further emphasizes that interaction in architecture involves intentionally exchanging information and physical performances between the building and its occupants. Consequently, interactive architecture aims to observe, learn, and respond appropriately. Fox and Kemp (2009) describe the interactive space as a fusion of embedded computation (intelligence) and physical components (kinetics), fostering adaptation in the context of human and environmental interaction.

Interactive architecture, influenced by the principles of cybernetics, has been leading to the development of various models emphasizing adaptation. For example, English architect Cedric Price (in collaboration with theatre director Loan Littlewood) proposed the Fun Palace project (1968), demonstrating the flexibility and adaptability of interactive reconfiguration of spaces (Mathews, 2005). Other conceptualizations of interactive architecture include a centralized feedback loop proposed by French architect Yona

Friedman (1972) and a fully distributed system presented by Charles Eastman (1972), a pioneer in design cognition.

In the 1990s, interactive architecture became more feasible due to advancements in both constructional and computing technologies (Fox & Kemp, 2009). Cost-effective construction techniques and accessible computing resources enabled designers to optimize performance through computational information and processing. Innovations in manufacturing, such as CNC machines, laser cutting, vacuum forming, and 3D printing, made prototyping more affordable, accurate, and efficient. These tools allowed designers to create precise three-dimensional models directly from digital software. Integrating computing systems and new fabrication techniques expedited the exploration and implementation of electro-mechanical systems in dynamic buildings through rapid prototyping. However, despite significant theoretical progress and numerous experimental initiatives (Beesley, 2020; Fox & Kemp, 2009; Fox & Yeh, 1999; Oosterhuis, 2003), the application of interactive and adaptive architectural systems remains limited primarily to conceptual designs and trial prototypes (Achten, 2019).

Nevertheless, two projects, a kinetic façade of the Al Bahar Towers (2008) and Mark Goulthorpe's (dECOi) Aegis Hyposurface (2001) are considered notable representatives of the responsive facade and interactive surface systems in this field. Al Bahar Towers in Abu Dhabi, designed by Aedas Architects, represents a dynamic shading system placed over the glass façade. Inspired by the Middle East traditional mashrabiya screens, folding panels passively open when exposed to direct sunlight (Cilento, 2012). They provide 20 percent of energy savings and 20 percent less carbon emission, reducing the plant capital cost by 15 percent (Fox, 2016).

The Aegis Hyposurface, on the other hand, is a kinetic interactive artwork designed by Mark Goulthorpe for the foyer of the Hippodrome Theatre in Birmingham (dECOi, 2011). As a programmable wall faceted by triangular metallic plates, it could respond to the stimuli of movement, sound and light from its surroundings using 896 pneumatic linear actuators and springs (Gruber, 2011).

2 Methodology

The project presented in this paper is a cone-shaped hexagonal electro-mechanical unit that functions as a three-dimensional aperture. Its diaphragm, made of tensioned opaque elastic fabric, opened and closed mechanically using custom-made linear actuators in response to sensing adjacent activity within the space. Each component's function was independently programmed and controlled by a microcontroller synchronized with human proximity. The design underwent iterative digital simulation and experimental prototyping that underwent multiple performance tests. Beyond merely creating a tactile mockup, prototyping was a proof of concept using off-the-shelf hardware mixed with materials and a fully functional unit cell built of accurately crafted parts.

2.1 Mechanical Parts

For the unit's structural integrity, the mechanical sections consisted of two hexagonal-shaped base frames with a central void attached parallel to each other at a distance. The movement of the three-dimensional aperture was generated by six wooden pistons that moved back and forth across the unit. The pistons were secured by 15-degree-tilted tubes toward the unit's center, resulting in a convergent motion. Consequently, their movement could produce open and closed functions. The rods measured 34 cm in length and had a linear travel range of 20 cm.

The apertures were considered closed when deactivated, so piston rods were initially forced out entirely toward the unit's front using extension springs. A spandex fabric was used to cover the unit and form the three-dimensional cone by attaching it to the apex of the rods and the perimeter of the frontal hexagonal base. Consequently, when the aperture was closed, the fabric was completely stretched. In order to open the aperture, piston rods were retracted using a DC electric stepper motor, specifically a NEMA 17 stepper motor with a holding torque of 0.59 nm.

The advantages of stepper motors are their simplicity, rugged construction that functions in almost any environment, high torque at the start and low speeds, low maintenance, and ability to operate in an open-loop control system. Moreover, the stepper motor has 200 steps per revolution and a step angle of 1.8 degrees, allowing it to provide precise rotation. If the motor is carefully sized for the application with regard to torque and speed, it can move and hold at one of these steps. Due to the motor's precisely controlled rotation, pistons could be moved exactly at a given distance. The further they moved in reverse, the wider the aperture became.

One of the most challenging aspects of designing kinetic components was achieving an equilibrium between the motor torque force and the sum of six extension springs to allow for reversible aperture opening. Although multiple prototypes were created through rigorous design iteration, three major development stages can be identified in which the mechanical part's functionality was enhanced. Using the Grasshopper plugin for Rhinoceros, the primary performance of every new development was digitally analyzed and modelled. Subsequently, a physical model was constructed to a specified scale to investigate and evaluate its functionality.

Step 1: In the initial prototype, six strings were pulled together by a single pulley attached directly to the motor shaft (Figure 1). Given that the torque of the stepping motor was 0.59 Nm, or 5.22 lbf.in, it was anticipated that six springs would be pulled together with approximately 4.8 lbf.in (0.8 lbf.in each). Nonetheless, the motor was incapable of pulling pistons. It was noted that attaching a pulley with a 3-centimetre diameter on a motor shaft with a 0.5-centimetre diameter reduced the force by a factor of one-sixth.

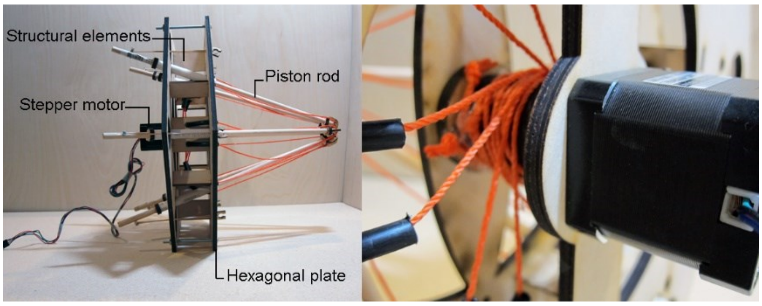

Figure 1. The initial prototype in step one, in which a single pully attached to the stepper motor pulled six strings of all pistons. Source: Youness Yousefi (2023)

Step 2: In the second design (Figure 2), the rotation torque force of the motor was increased by designing and adding different spur gears. The central pulley was attached to a large gear with 160 teeth driven by a small driver gear with 20 teeth attached to the stepper motor shaft. The gear ratio is calculated as follows:

$$Gear\ ratio = \frac{\text{No.of teeth on the driven gear}}{\text{No.of teeth on the driven gear}} \quad (1)$$

Therefore, the gear ratio was 1:8, resulting in an eightfold increase in transfer force while the pulling speed decreased by the same factor. In addition, plastic pulleys were added on corners along the strings' path to reduce friction. However, the motor struggled to pull six pistons through their travel path and thus extend the springs only halfway. Consequently, the motor could only open the aperture up to midway effortlessly. In the second half, it skipped steps and frequently stopped, and the movement was neither complete nor smooth. It was noted that the springs' elastic potential energy increases proportionally during spring extension, which explains the observed phenomenon. The elastic potential energy of a spring is equal to the work required to extend it, which depends on the spring constant k and the distance stretched. The force needed for stretching a spring can be calculated based on Hooke's law as follows (Young et al., 2002):

$$F = -kx \quad (2)$$

Where F is force (N), k is spring constant (N/m), and x is the displacement (m). According to the equation, the more string stretches, the more force is required. Thus, more power was needed to open the aperture toward the complete opening.

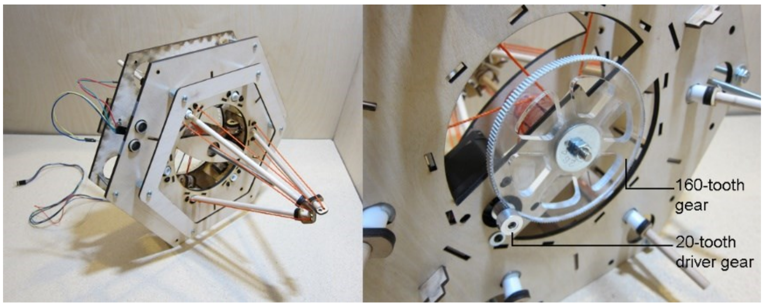

Figure 2. The prototype in step 2 with enhanced motor torque using a gear ratio 1:8. Source: Youness Yousefi (2023)

Step 3: Using a movable pulley provides a mechanical advantage of two, reducing the force required to lift an object by half (Figure 3), whereas a fixed pulley does not affect the energy required to raise the object (Fritts; et al., 2005). Multiple pulleys facilitate a greater mechanical advantage when combined. Therefore, a set of compound pulleys comprising two movable and two fixed pulleys was employed to reduce the total force required to draw the piston rods by a factor of 1/4 (Figure 4). Therefore, the motor was able to steadily draw back the six pistons and open the aperture. If the windings are energized, the stepper motor maintains its maximum torque at a stop. Therefore, the motor could sustain the aperture open at any position with stretched fabric and extended springs owing to its high holding torque.

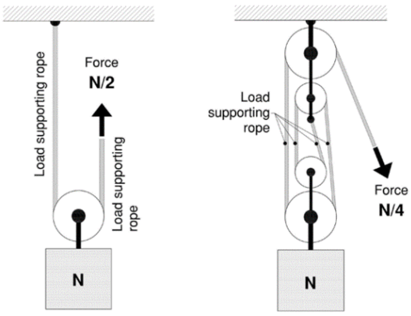

Figure 3. The mechanical advantage of a movable pulley is two: halving the force required to elevate an object. Source: Youness Yousefi (2023)

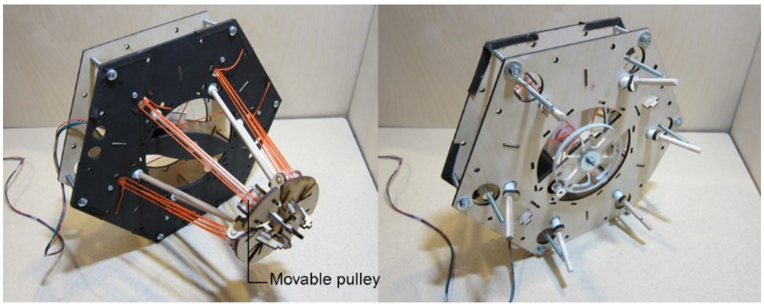

Figure 4. The prototype in step 3 has compound pulleys consisting of two movable and two fixed pulleys to each piston rod. Source: Youness Yousefi (2023)

2.2 Controlling Mechanism

Each unit cell had a separate controlling system comprised of a microcontroller and an ultrasonic distance sensor, which worked independently from the adjacent units. An ultrasonic distance sensor was used to constantly scan the area in front of the unit to detect an approaching object and determine its distance from the unit cell. The unit's function was programmed using an Arduino microcontroller to interact with the approaching object and the stepper motor in a real-time feedback loop. After each activation, the control system closed the aperture and reset the movement process while recording the number of activations in an accumulative fashion. The aperture is performed based on converting the distance to the object into moving steps of the stepper motor through digital pulses. The program triggered activation with a minimum opening once detecting someone at a distance of 2 m. When a person moved towards a unit, the aperture opened in inverse proportion to the person's distance to the unit and became fully open when the distance was 20 cm.

3 Results and Discussion

Initially, a three-dimensional model of an interactive surface with aggregated units was modelled, and its performance was simulated in the grasshopper, a parametric virtual modelling plugin for Rhinoceros (Figure 5). A physical prototype of each unit was built to calibrate the controller system's functionality in the long run by synchronizing its mechanical performance and a moving object. The aperture function was observed to deviate slightly after several open-close cycles at maximum speed, caused by skipped steps in the stepper motor rotation. This issue was resolved by slightly reducing the motor's speed below the maximum limit.

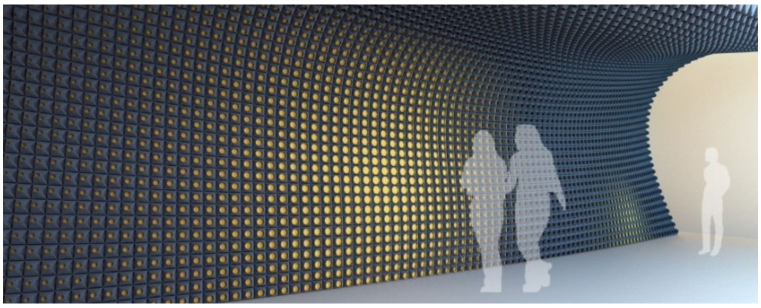

Figure 5. The performance simulation of the interactive wall system illustrates localized windows adjacent to the occupants within the space. Source: Youness Yousefi (2023)

Accordingly, a prototype consisting of five modules was constructed and situated in an area that experiences regular daily foot traffic (Figure 6). For thirty days, we monitored and assessed each unit's mechanical functionality and durability within the system. Upon analyzing the recorded data of the frequency of aperture operations, it was observed that the custom-made linear actuators exhibited the highest susceptibility to damage among all the components of the units. Consequently, two units stopped functioning due to actuator deficiency after 73 and 89 cycles of openings and closings in three days. The remaining three units persisted in operation but began producing audible vibrations after three weeks. This was attributed to the minor displacement of a few actuators, resulting in friction.

The efficacy of the actuators' performance relies on the PVC tube sleeves that enable the linear movement of the wooden pistons without using any lubricant. Frequent movement of the piston leads to wear the wood and generates heat that causes abrasion of the inner surface and bending of the tubes. In long-term operation, these parameters not only prevent pistons from moving smoothly inside the holding tubes but also cause more damage to the actuators. In addition, more force is needed to open and close the aperture.

The material arrangement of the prototyping was based on the available off-the-shelf materials. A material compatibility study is required for the more robust function and durability of the actuators.

Figure 6. The final prototype, comprised of five modules, was placed in an area with daily foot traffic. Source: Youness Yousefi (2023)

The performance of the assembled surface of units can be considered within different scenarios, as a building envelope responds to the users' presence and environmental conditions. Compared with the existing interactive and responsive architectural systems such as Al Bahar Towers and the Aegis Hyposurface, which are considered either heavy mechanical additions or internal interactive surfaces with linear predesigned performance and high maintenance requirements, the proposed design offers several advantages for the experience and comfort of building occupants. When occupants in the space approach the envelope, a localized window is created against their position during their presence to provide light for the inside or a framed view of the outside. Furthermore, the cone shape of the aperture prevents glare by breaking the direct sunlight and creating diffused daylight for the interior activities of inhabitants. In this case, the surface system is controlled domestically.

On the other hand, the building envelope can regulate the internal conditions by entering or blocking the light and wind to provide comfort for the inhabitants. For example, during summer, the apertures can also be programmed to decrease the direct sunlight and lower the heat gain in the spaces of the buildings by reducing the maximum opening of the aperture. Additionally, to cool the room, the envelope can make a few openings at specific locations during the night to allow air circulation in the building through natural ventilation. In this case, the envelope system is controlled globally.

4 Conclusion

This paper presents an innovative approach integrating computation and kinetics to create an interactive pixel unit. We offer the design of an electro-mechanical unit that transforms an iris's two-dimensional open-close function into a three-dimensional convergent movement. The open-close function of the three-dimensional aperture was provided by a conical movement of a stretchy fabric using six custom-made linear actuators. The aggregation of the units forms a dynamic surface which can be installed inside, outside, or on both sides of a transparent (e.g. glass) wall. As a result of this dynamic interaction through a live feedback loop, a localized window will be formed against each person approaching and will be maintained while the person remains within a certain distance to the surface. The cone shape of the aperture prevents glare by diffusing the direct sunlight and provides indirect daylight for occupants' activities.

Despite the promising perspective of IA, yet, considering its novelty, adaptive buildings' design-to-delivery process should be developed to yield an effective interdisciplinary collaboration between architects and engineers. Furthermore, due to the lack of an available manufacturing stream, all functional parts are currently custom-made and project-based; thus, their construction is costly. By establishing best practices and adapting new fabrication technologies such as 3D printing in this field, components of dynamic complex systems should be manufactured with a mass customization process.

This study reflects shifting perspectives that architects are exploring as they strive to create interactive, responsive structures adaptable to the individual needs of users and the requirements of the dynamic environment (sun, wind). This approach to design, where adaptability is one of the leading design goals, necessitates a new approach to design that fully incorporates time and change into the design process.

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