Using parametric BIM integration for prototyping future responsive façades

Zaki Mallasi

Assistant Professor, College of Architecture and Design, Effat University, Jeddah, Saudi Arabia

Architectural BIM Lead, AECOM, Baltimore, MD 21202, USA, zaki@iconviz.com

Abstract

Throughout history, architectural façades have been designed to respond to environmental, social, and functional conditions, among other considerations. Advances in Digital Design Computation (DDC) emerged as an essential support for exploring and creating contemporary architectural façades. Current research attempts to find a responsive kinetic façade have revealed different methods of integrating kinetics into the physical façade. However, some case studies indicated that physical façades struggled to achieve the anticipated kinetic responses in the constructed façade. In addition, the process is formal, prescribed, lacks flexibility and can only assist design visualisation. As a consequence, the challenges in understanding the process of connectivity between digital/physical kinetics are important to address in the early design stage. Digital and physical façade prototypes would allow designers to test the qualities of such systems before constructing a full-size mock-up, and to discover new modes of parametric design thinking in architecture.

In this work, we report on the ongoing development of a custom add-on utilising Autodesk ® Revit application that connects the kinetic properties of digital and physical models to control a dynamic façade. We deployed the Revit Application Programming Interface (API) C# programming to manipulate the kinetic response through linear actuation. The system framework proposes a practical mechanism connecting solar exposure values to a Building Information Model (BIM). In this process, we used Arduino Mega board, servo motors, tooth-beam and tensile-fabric material to construct the small physical prototype and programme its automation.

While adding to previous research, we tackle three challenges. The first is to dynamically harness the response mechanism of kinetic façade so as to avoid uninformed design decision-making. The second is to map the digital/physical kinetic properties in terms of modelling, process, and function. The third is to assess the benefits arising from our approach of connecting the BIM parametric model with physical prototypes. Our experimental project demonstrates how data could be exchanged between the digital and physical façade models. We conclude by offering observations from this work on how BIM parametric modelling with design computation could influence the future direction of kinetic façade systems.

Keywords

Parametric Modelling, BIM, Kinetic Façade, Design Computation, Arduino, Prototypes

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1 INTRODUCTION

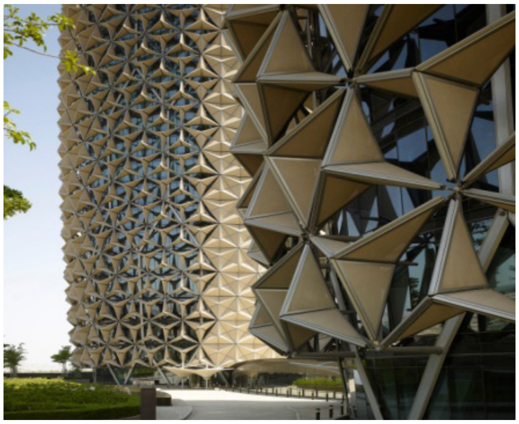
A building envelope, or a façade, has a considerable influence on the way we perceive the architectural quality and performance of buildings. To some extent, there has been a leap of interest in recent years towards creating façade elements with responsive properties that meet both aesthetic and environmental design goals (Sharaidin & Slaim, 2011). In vernacular architecture, traditional features like the Mashrabiyas (or sun screens and shading devices) are designed with geometrical characteristics and systems that reflect a specific culture, while shielding the building from harsh climates. Using manual mechanisms, a building's occupants can adjust the geometrical characteristics of the façade elements (e.g. open/close, stretch/retract, rotate, twist, etc.) according to the sun position to provide optimum shading (Bader, 2010).

Several case studies in engineering and architecture reported some drawbacks in the use of manually adjustable building façades, as well as their responsive systems. According to Loonen, Trcka, Costola, and Hensen (2013), the existing built projects (e.g. American Pavilion, Expo67, 1967; Institute de Monde Arabe, 1987; Kiefer Technic office building, 2010; and Al Bahar Tower, 2012) that use responsive façades are under-researched in terms of demonstrating how to achieve building energy optimisation (see Fig. 1). For such projects, there is clear reference in literature to the common problems faced by these façades, such as:

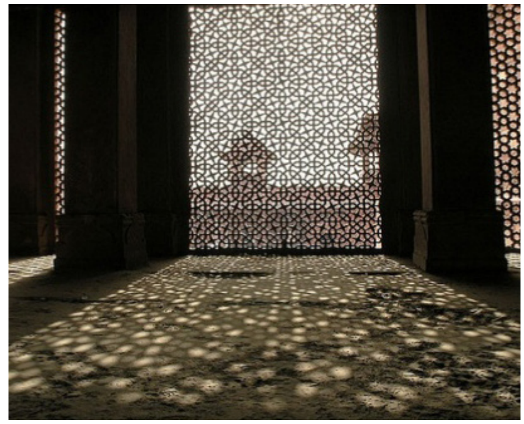
- Projects are yet to be constructed simply (Linn, 2014) and the process of manipulation is extremely underdeveloped.
- A motor mechanism that was controlled by 600 motors constantly failed during the operational of the building (Massey, 2006).
- Dynamic moving elements in responsive systems are logistically complicated, too slow, and have high maintenance costs.
- There is minimal discussion about the impact of the kinetic and the composition of the façades in terms of their environmental conditions.
- Although the outcomes of real-life case study projects indicate creative digital design processes, the façade performance results are rarely published in scientific literature (Loonen et. al., 2013).

The kinetic façade behaviour is an emerging idea which is rooted in the façade panel component. It is a performance-based design approach that assumes every component is adjustable according to its performance goals (e.g. environmental, functional, aesthetic, privacy, etc.). John Frazer (1995) in his book "An Evolutionary Architecture" explains that new forms of responsive structure emerge on the basis that flexible façade components constantly adapt to the surrounding changes. Each component is supported by use of receptors and actuators, which control the transformation of the façade components. A truly responsive structure could be established in a two-way relationship between the different conditions, façade structure, and the user (Kolarevic, 2014). The idea that buildings are "alive", "adaptable", "evolving", "flexible", and "intelligent" have profoundly influenced the architectural discourse of the 21st century and continue to do so.

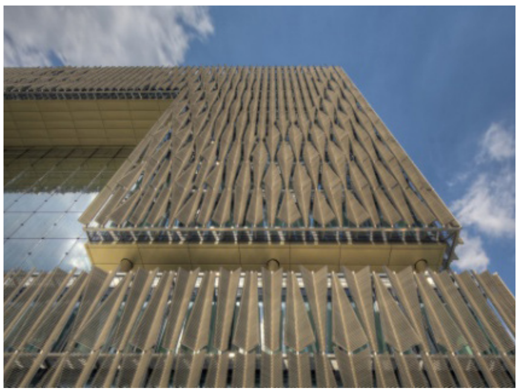
Traditional building façades essentially face different conditions that are transitory and constantly changing. Tashakori (2014) writes about common drawbacks of traditional building façades in that they are all rigid and resistant to design conditions in a static way. As a result, it may be argued that conventional buildings equipped with "static" façades configuration may not perform sufficiently well as the conditions change. The author suggests the need for responsive façade elements that constantly adapt to the changes in their environment.



Al-Bahr Tower in UAE (AEDAS UK)



Mashrabya Screen



ThyssenKrupp Quarter in Germany (JSWD Architekten, Chaix & Morel et Associés)

One Ocean Thematic Pavilion in South Korea (soma)

FIG. 1 Traditional Mashrabiy and modern kinetic façades projects (source: http://www.archdaily.com).

This paper presents the research outcomes of the first phase experiment, examining a dynamic self-updating loop when manipulating the individual façade elements. There was further motivation to create a small prototype as a platform for future studies, on the basis of this "dynamic" visualisation approach. It is also necessary to highlight research output that encourages further integration of DDC that drives prototyping of a parametric BIM façade with self-updating features (Harfmann, 2012). This experiment is further assisted by: parametric modelling, BIM, receptors technology, and the utilisation of digital/physical prototyping technology.

2 KINETIC FAÇADE RESEARCH METHOD

It is important to give a definition of the "Creating-Making" method used in this ongoing experiment. This method aims to apply a prototyping process to understand the mechanism of the proposed responsive kinetic façade system. "Creating-Making" closely relates to the traditional design process with loops of system feedback in which geometry and objects, real or virtual, continuously inform each other during the ongoing experiment. The method is not entirely new in the design process, but it is flourishing as the result of the development of an inexpensive open source microcontroller board called Arduino UNO (see Fig. 2 below). Since its release, it has enabled design enthusiasts worldwide to create all sorts of interactive objects and responsive environments (Kolarevic, 2014). In doing this, digital receptors, maturity in parametric modelling with visual programmable geometry enriched data exchange between the responsive façade system and the digital model (Kensek, 2014).

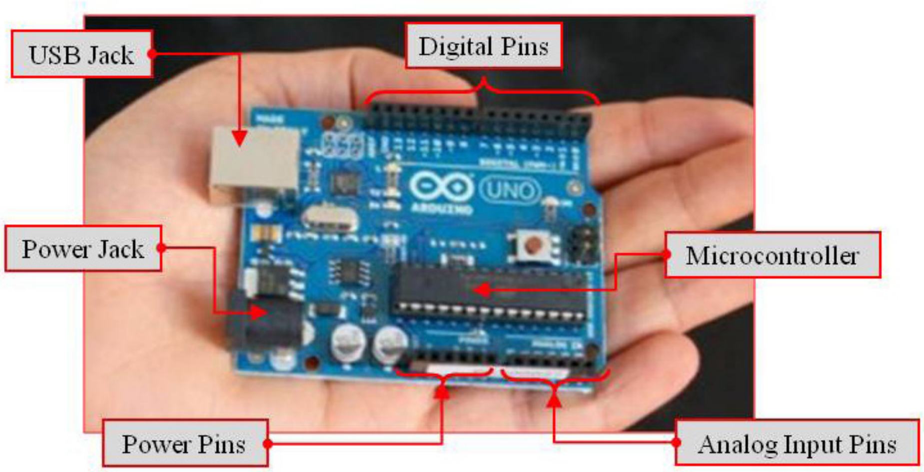


FIG. 2 The Arduino UNO microprocessor board (image by www.sciencebuddies.org).

2.1 CREATING AND MAKING LOW-COST PROTOTYPES

Many references have been made to similar research attempts relating to dynamic façades using programming scripts, DDC, and the hardware automation process, most notably by Kensek (2014), who attempted to evaluate - in eight case studies - the connection of a simple BIM model, Arduino, and environmental sensors to control the 3D model of the sunshade. In the examples, a movable light shelf is adjusted using Rhino and Grasshopper with Arduino, with support from DIVA daylight analysis. In addition, other examples utilised Revit and Dynamo as links between the 3D model, and Arduino to control the model parameters. Regardless of the numerous attempts, our approach in particular explores three important aspects:

- How the physical model objects and digital geometry are synchronised to adapt and respond to data.
- How to map the script program procedure that triggers the responsive action.
- How to define the time-scale for a response in the prototype, which plays a major role in creating an effective a kinetic system.

As we begin exploring this approach, our small dynamic façade prototype experiment revisits the dataflow and processing of a responsive dynamic façade. As discussed by Sharaidin (2014), this is mainly because static façades contrast with the design of dynamic façades, which involves various configurations. It is within this context that the "Creating and Making" approach, and the exchange of dataflow into the early design phase, require careful representation and change to the designer's mind set in order to achieve a high-quality end product (Fig. 3). Furthermore, there is a need to investigate how effectively DDC tools can link with the kinetic façade mechanism. As a consequence, the process of implementing DDC optimisation for dynamic façades is underdeveloped and requires further testing and evaluation.

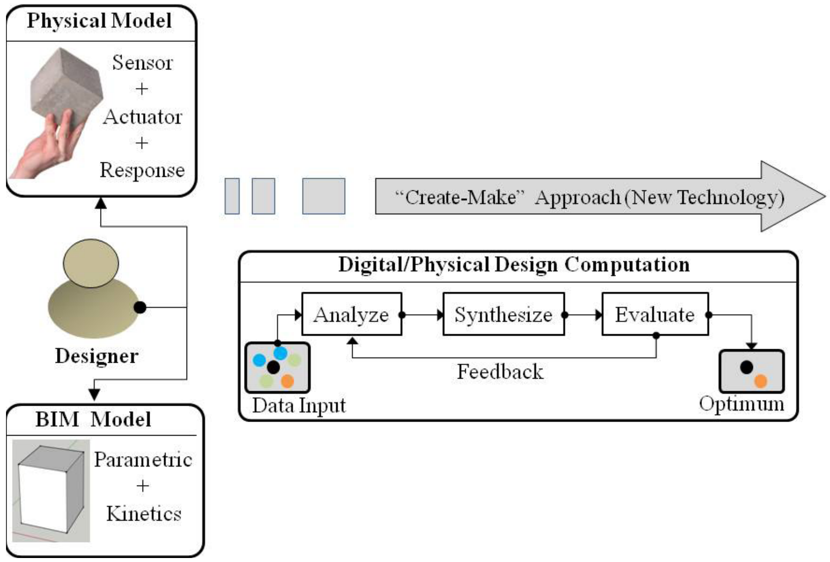


FIG. 3 A Create-Make mind set approach and discovery process.

3 KINETIC FAÇADE RESEARCH METHOD

The experimental prototype is for a small façade and the approach is to automate data flow with a dynamic self-updating loop. In Phase (1) of this research, we aim to achieve the kinetic transformation by mapping the Revit digital façade panel properties to the real small prototype according to solar exposure (Fig. 4). In Phase (2), the real small prototype components dynamically change according to sensor solar exposure values which "Self-Update" the digital façade panel.

In relation to the exchange of data flow in the kinetic façade, this prototype expands the BIM working environment, while taking into consideration the façade's geometrical properties, for example the panel shape and size, thereby reflecting the features of the design intent. We created a digital-hardware-physical computation framework between the prototype parts and the set of data-flow involved in the kinetic movements. As shown in Fig. 4 below, this experiment is an exploration of a new approach to implement our proposed "Self-Updating" BIM model for an effective analytical design process of responsive façades that react to a variety of conditions (e.g. solar exposure, function, and aesthetics).

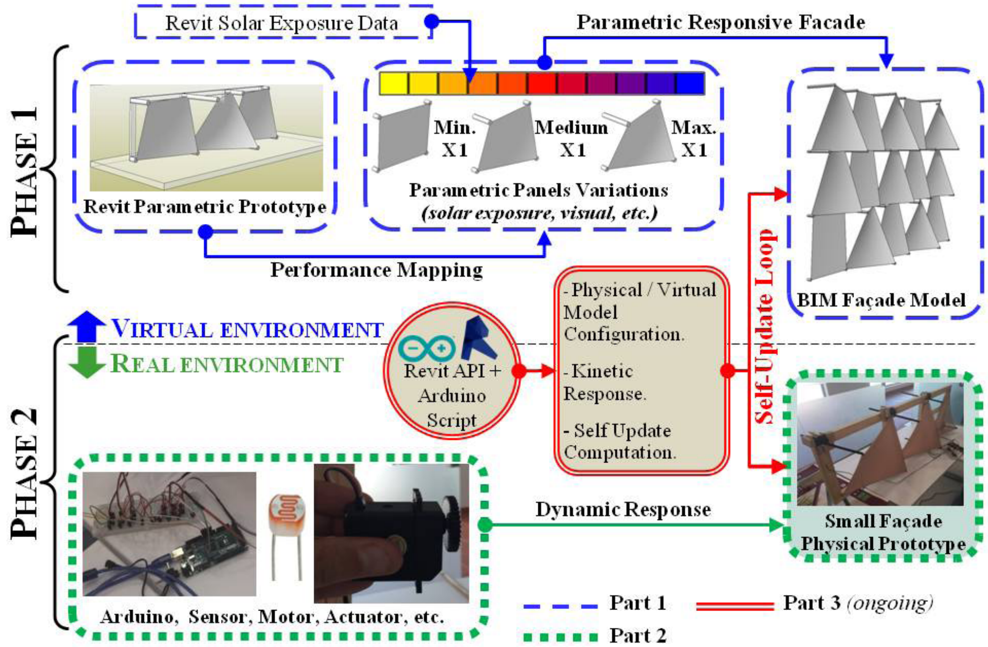


FIG. 4 Proposed research framework self-updating.

3.1 THE SMALL PROTOTYPE PARTS

Over the course of developing the conceptual framework shown in Fig. 4 above, we realised the difficulty of installing an actual scale 1:1 prototype on the entire building façade. The following sub-sections describe the three main parts intended to represent a dynamic façade development framework in accordance with the proposed "Creating-Making" design process. The resulting visual expression of the façade is driven by both user input and simulated exterior environment.

3.1.1 PART (1) – Parametric Façade Panels Utility

This part utilizes Revit® BIM parametric modelling to construct 3D façade panels prototype. The core concept in parametric modelling is that objects and sub-objects are associated with one another through parametric rules that keep their association within one framework. A single change to one parameter would affect the panel properties.

The panels are assigned an "X1" parameter to control the stretch/retract distance, and consequently affect the panel opening area (Fig. 5, c). Every "X1" parameter within the Revit® façade panel response is assumed to react to the variation of the solar exposure produced by the Revit® Solar Analysis plug-in. Using the colour-range values from the solar analysis, the three façade configurations produced are:

- **Small Opening Size** = High Exposure = Yellow Colour = Minimum X1.
- **Medium Opening Size** = Medium Exposure = Red Colour = Half X1.
- **Large Opening Size** = Low Exposure = Blue Colour = Maximum X1.

Furthermore, the opening size is determined by a range of "X1" parametric values. The "X1" parameters are dimension "length" type Revit® parameters. We implemented the change of "X1" values and rule using Revit ® API C# programming that figures the solar exposure range value (low, medium, and high. In a conceptual manner, the solar exposure images are bitmaps made of pixels in which each pixel's Red Green Blue (RGB) value can be obtained in order to evaluate the solar exposure range values. Such RGB values of a solar exposure image were implemented using the C# programming language available in the Revit API.

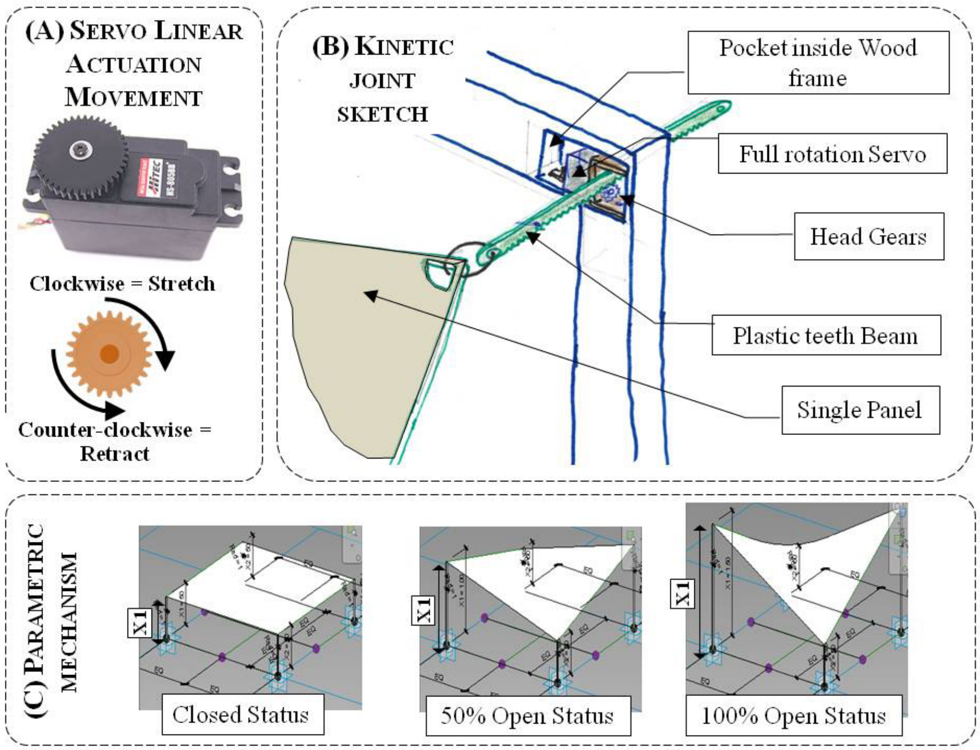


FIG. 5 Sketch of the joint assembly idea with the motorised actuation parts.

3.1.2 PART (2) – Physical Façade Prototype Assembly

A sketch illustration of the physical prototype parts is shown in Fig 5, b. above. In reality, the panel's surface would be constructed from a stretchable cloth-like fabric as an affordable material. When experimenting with a responsive façade prototype, the choice of materials was a major factor in assessing its suitability. Materials such as wood support frame and flexible low-cost tensile fabric are adapted in the prototype to mimic the structural/mechanical system. In real buildings, the high tensile strength function would be achieved using a composition of glass fibre-reinforced polymers, which also give them a low bending stiffness and allows for large reversible elastic deformations. The stretch/retract motion mechanism consists of motorised actuation assembly attached to the façade panels. The combination of the tensile-fabric panels, wood frame, strings, cords, gear head, actuating beams and the servos are arranged so that the panels can easily make a linear kinetic by actuating the servos.

Each façade panel relies on two joint assemblies to ensure the actuation assembly fitted within the prototype as an adjustable shading device. These panels can be adjusted and reconfigured to achieve the goal of having a "Self-Updating-Loop" responsive façade feature. The clockwise/counter-clockwise movement of the kinetic panel is based on an actuation mechanism using a rolling gear beam attached to full-rotation servo motors (See Fig. 5, a). Through exploration during the construction of this prototype, we introduced a pocket hole to house every kinetic joint of this prototype. This allowed us to achieve a stable movement with reduced vibration due to the actuation mechanism.

The two full-rotation servos control one façade panel through the Arduino programmable board. Every pin represents a channel of communication between the computer ports from which input information is sent to the servos that are connected to the Arduino board using jumper wires to transfer signals to the microprocessor. The linear actuating arm maximum and minimum ranges positions are defined for each servo. The Arduino programming script translates an electrical pulse delay to control the continuity of rotation and speed of the servos. We experimented with this delay through trial and error, in order to figure out the conversion of rotation cycles to translate to specific stretch/retract distances. We attempted a medium speed rotation in order to observe the kinetic movement and the notion that some servos can get damaged in high speed rotations.

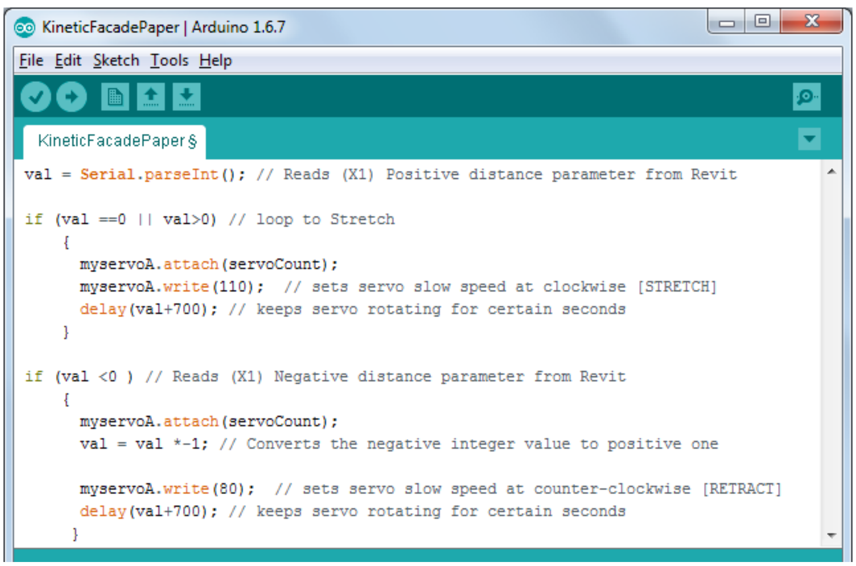


FIG. 6 Arduino script defining conditions for stretch or retract mechanism.

3.1.3 PART (3) – Digital and Physical Kinetic Computation

This is a core part of the project system environment development in which we created an Arduino script to execute the kinetic response as well as a simple C# Graphical User Interface (GUI) in Revit API that accepts actions made by users. As mentioned previously in this paper, we are currently discussing only phase one of this ongoing research, which is the kinetic system from Digital to Physical. This will be discussed, while simultaneously describing the data-flow process, in the following:

— **Arduino Script**: evaluates two possible scenarios for positive or negative (X1) parametric integer values sent from Revit to Arduino via a USB serial communication port connected to the computer. In this study, this connection is the key part in sending/receiving data between the Revit BIM prototype and the physical one. The general structure for the script is shown in Fig. 6 above, in which the actuation direction, speed of actuation and assigned servo motor pin number are controlled. As the servo motor rotates, it will drive the tooth-beam either to stretch or retract a certain calculated distance. It is important to mention that each servo motor operates sequentially after the previous one and not simultaneously. This development realised such drawback issues due to the maximum voltage required to supply each servo motor.

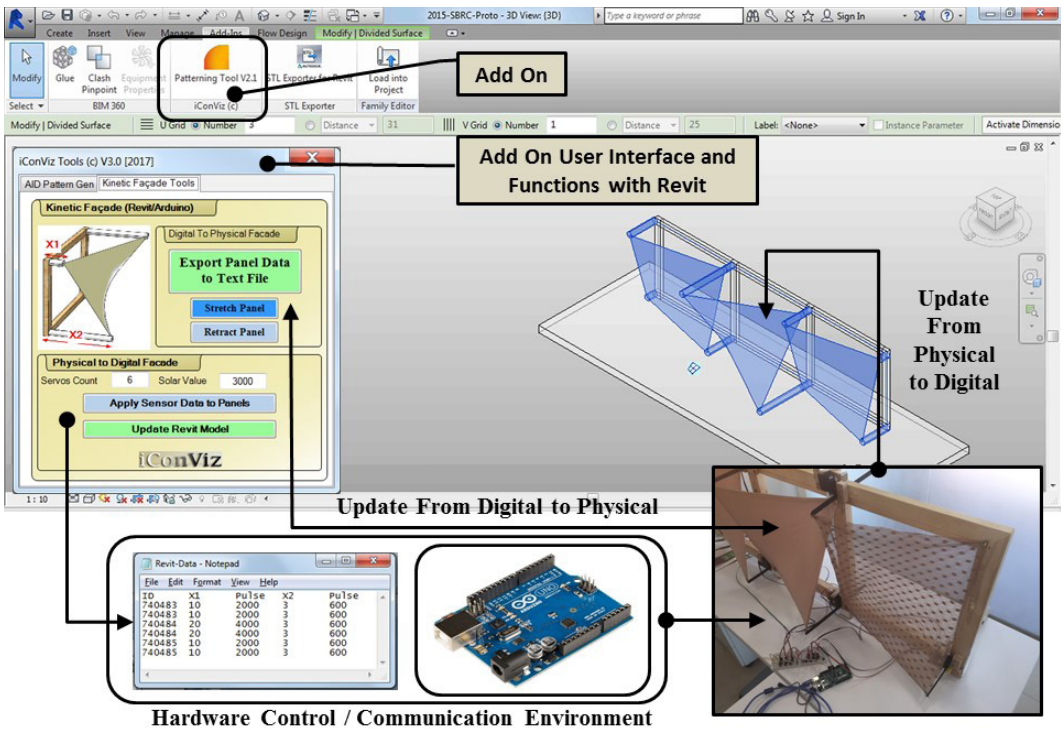
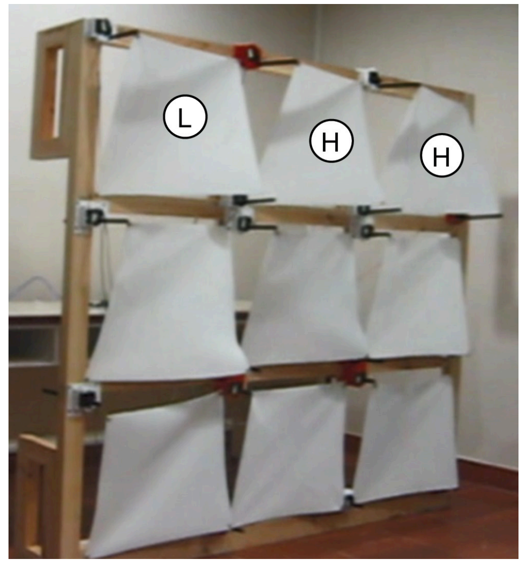


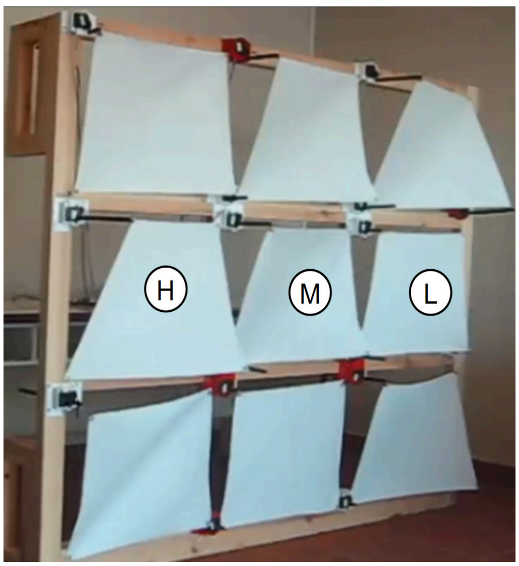
FIG. 7 The Revit custom add-on and graphical user interface for kinetic façade.

— **Custom Built Revit Add-On**: This was designed during the course of our work using Revit API C# programming in order to achieve the translation from digital to physical (and vice versa). In terms of achieving the first phase of this research, the add-on logically defines the behaviour to manipulate/read "X1" parametric panel input values. As illustrated in Fig. 7, the method of communicating the digital/physical façade properties is through sending digital analog pulse to the physical façade prototype. The add-on makes use of a custom DLL file as communicating the actuation configuration of the digital façade properties mapped onto the physical prototype. This integration involved automating data transfer from the digital to the physical façade by means of exporting façade panel parametric properties "X1" formatted to their relative analog pulse rate. The calculation of the solar radiation variation occurring at different scenarios was obtained from the solar image that was exported from the Revit Solar Radiation tool. The physical façade panel configuration is updated constantly using the custom add-on in accordance with different solar radiation studies. As previously mentioned, the physical prototype is controlled by the digital analog pulse sent from the custom add-on to Arduino board as a kinetic response for either the increase or decrease of "X1" parameter.

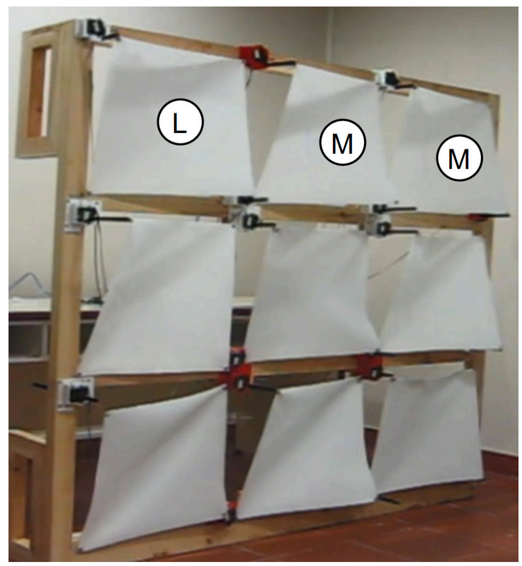
1 *Closed Panel Status*



2 *Test Run (1) [Low-High-High]*



3 *Test Run (2) [High-Medium-Low]*



4 Test Run (3) [Low-Medium-High]

FIG. 8 Various Test Runs for the stretch and retract mechanism.

4 PRELIMINARY EXPERIMENT OUTCOMES (DIGITAL TO PHYSICAL)

A series of six test-run experiments have been initiated to illustrate the application and evaluate our proof-of-concept kinetic façade prototype during the early stage of façade design. Our aim is to simulate a real world environmental condition using simple solar exposure range values: low, medium, and high. The experiment mapped the variations from the digital to the physical in the resulting façade panel movement for each stretch/retract test-run based on input from four solar exposure analysis images. We then evaluated the resulting façade's responsiveness and compared them in terms of motor rotation movement, form/shape flexibility, and digital to physical design similarity. The test-runs outcome comparisons are shown in Fig. 8.

In all test-runs scenarios, we used the physical wood prototype frame structure and attached to it three panels made of light tensile fabric to represent an exterior building façade. At this stage of the research, the main aim was to examine the efficiency and suitability of the kinetic mechanisms. The table in Fig. 8 shows the three assessments and a summary is provided below.

- **Assessment (1) – Motor Rotation Movement**: as the user initiates a stretch/retract action, the servo motors rotate according to the required directions (i.e. clockwise or counter-clockwise) and at a uniform speed. The opening size updates slowly due to the increase/decrease change mechanism. There were some minor issues with a delay in the movement of some servos, of less than a second, which caused a variation in the rotation speed. This issue is attributed to material-to-material friction, which affects the repetitive rotation movement. The servo motor achieved the necessary 360° rotation and in turn the tooth-beam actuates to enable the panel to attain a low, medium, or high position. Allowing the users to change the speed of motor rotation was not the primary objective in this experiment because it depends on the speed of response needed, prototype cost, panel size and weight. In general, the overall reliability on the servo motor within the suggested kinetic arm joint remained stable for a period of time.

- **Assessment (2) – Form/Shape Flexibility**: This is a major challenge in the construction of a kinetic façade prototype, as it reacts to input/ data acquisition to create its flexible movement. The experiment led to permitting the movement of the single panels and thus allow for flexibility and interactive transformation. The tensile fabric-material showed various responsive kinetic transformations for use in the kinetic façade. As the façade panels changed shape, the panels demonstrated an elastic and flexible surface structure movement with few mechanical problems. Most importantly, the problem of friction during the operation of the kinetic façade prototype is reduced as result of using the lightweight panel material and slow actuation speed which reduces dependence on heavy mechanical components. Since façade responsiveness in this experiment needn't be in real time, it has been calibrated to respond over larger time scales, like every hour at best. In the future, a higher voltage of electricity will be needed to achieve high flexibility.

- **Assessment (3) – Digital to Physical Design Similarity**: Through this exploration, we observed the visual similarities between a parametric façade model and behaviour of the physical façade. This exercise consisted of manipulating the digital façade geometry from solar exposure image input and mapping the visual effect on the physical prototype panels. The observed results showed that the design similarities between digital and physical have the capacity to create matching façade patterns' configuration. This effort to map visual similarities is noticeably generated by the kinetic actuation actions. The essence of simplest pairing of façade panels can generate interesting design alternatives with dynamic façade pattern. Specifically, the custom add-on employed here could quickly generate different versions of the façade geometry for various purposes. In this way, designers can interact with the digital form of the façade geometry and the density of its pattern, and thereby obtain visual feedback. In addition, one can use the resulting parametric model properties to validate the design with a more accurate kinetic exploration of visual and appearance.

5 CONCLUSION

Since digital design technology is becoming more empowering to the design process, we were able to implement them to create a responsive façade in a different way than was previously possible. In doing so, we took advantage of the rich parametric information in a BIM façade model to understand the kinetic translation process to a physical façade prototype. For this purpose, this small project explored the principles and mechanisms in the design workflow through mixed digital-physical prototyping. Many practitioners and architecture educators consider "Creating-Making" a critical approach of the learning environment, as part of providing the user with knowledge and practical skills. It should allow the users to concentrate on DDC as a comprehensive process from the beginning of initial design concepts and ending with a high quality design product.

A main aspect of this proposed system framework has seen the development of a custom add-on tool with algorithm to drive the kinetic façade generation and exploration. In this regard, the add-on controlled the digital/physical kinetic parts to simulate the surface of the façade under different conditions. One of the things we learned from exploring the digital versus physical realm is that the manual construction of prototypes is also necessary. The user interaction and sharing of digital information between software, hardware, and kinetic building components is a challenging process that requires physical prototyping. The custom add-on was necessary to push the development of the experiment in kinetic architecture forward.

The experiment presented here is considered to represent the completion of our first phase of design and development (digital to physical). Although the second phase (physical to digital) of research is an unfinished feature, we believe that the underlying system framework and add-on are adequately developed to achieve our goals. The system framework implemented in this work is the starting point of our efforts to develop a connection to the BIM model from the physical model.

Acknowledgment

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