INTEGRATING PHYSICAL AND DIGITAL PROTOTYPES USING PARAMETRIC BIM IN THE PURSUIT OF KINETIC FAÇADE

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Abstract. Architectural facades are designed to respond to environmental, social and functional considerations among others. Advancements in Digital Design Computation (DDC) emerged as an essential support for exploring and creating contemporary architectural facades. Current research into responsive kinetic facade suggests different methods of integrating kinetics into physical facade. However, research indicates that physical façades struggle to achieve the anticipated kinetic responses. In addition, the process is formal, prescribed, lacks flexibility and mostly assists the designer in the visualization of design. Consequently, the challenges in understanding the creative process that mediates 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 system before constructing full size mock-ups and discover new modes of parametric design thinking in architecture.

We report on an ongoing development of a custom add-on utilizing Autodesk ® Revit application that connects between the kinetic properties of digital and physical model to control 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 an Arduino Mega board, servo motors, tooth-beam and tensile-fabric material were used to construct the small physical prototype and program its automation.

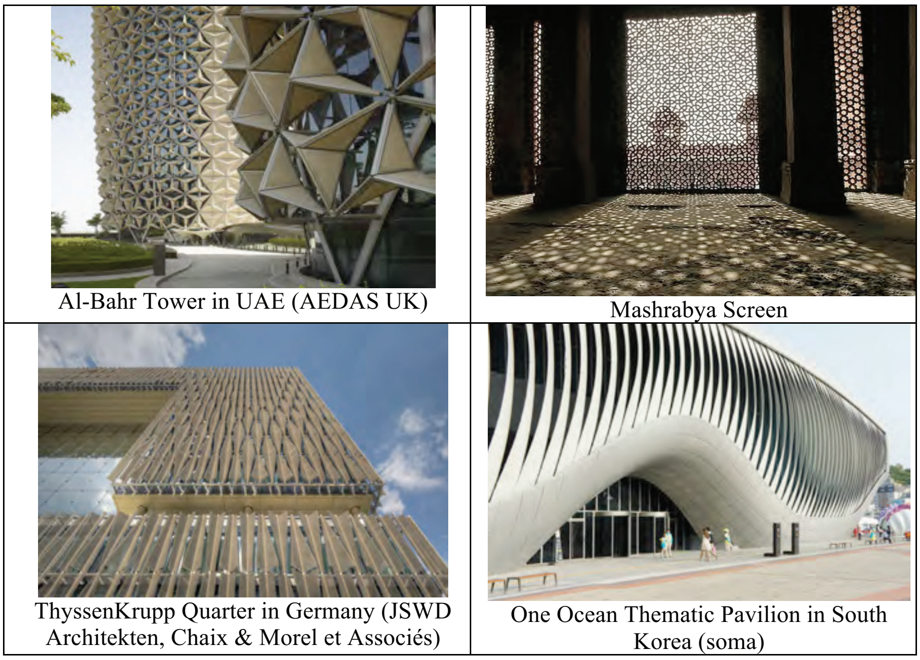
We tackle three challenges. The first is to dynamically harness the response mechanism of kinetic façade so as to avoid uninformed design decision making. The second is to map the digital/physical kinetic properties in terms of: modeling, process and function. The third is to assess the benefits from our approach of connecting BIM parametric model with physical prototypes. We conclude by observations from this work on how BIM parametric modeling with design computation could influence the future direction of kinetic façade systems.

1. Introduction

Building envelopes, or a façade, have a considerable influence on the way we perceive the architectural quality and performance of buildings. Recently, there has been a increased interest in creating elements of the facades with responsive properties to meet the aesthetics 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 system to reflect specific cultural aspects while shielding the building from harsh climate conditions. Using manual mechanism, the occupants can adjust the geometrical characteristics of the façade elements (e.g. open/close, stretch/retract, rotation, twist, etc.) according to the sun position to possibly provide optimum shading (Bader, 2010).

Several case studies in engineering and architecture reported some drawbacks from manually adjusting building facades as well as their responsive systems. According to Loonen *et al* (2013), the current built projects (e.g. American Pavillion, Expo67, 1967; Institute de Monde Arabe, 1987; Kiefer Technic office building, 2010; and Al Bahar Tower, 2012) using responsive facades are under researched when demonstrating how building energy optimization is achieved (see figure 1). For such projects, there is clear reference in literature to the common problems the facades are facing such as:

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



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)

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

The kinetic facade behavior is an emerging concept rooted in the façade panel component. It is a performance-base design approach that assumes every component is adjustable according to its performance goals (e.g. environmental, functional, aesthetics, privacy, etc.). John Frazer (1995) in his book "An Evolutionary Architecture" explains that new forms of responsive structure emerge on the basis that flexible facade components constantly adapt to the surrounding changes. Each component is supported by use of receptors and actuators which controls the facade components transformation. A truly responsive structure could be established in a two-way relationship between the different conditions, facade structure and the user (Kolarevic, 2014). These ideas 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 facades in essence face different conditions that are transit and constantly changing. Tashakori (2014) writes about common drawbacks of traditional buildings facades in that they are all rigid and resistant to design conditions in a static way. As a result, it is arguable that conventional buildings equipped with "static" facades configuration may not perform sufficiently as the conditions change. The author suggests the need for responsive facade elements that are constantly adapting to the changes in their environment.

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

2. Kinetic Façade Research Approach

It is important to acknowledge that the "Creating-Making" approach used in this on-going experiment aims at understanding the mechanism of the responsive façade. "Creating-Making" is not entirely new in the design process but it is flourishing as a result of development of inexpensive open source microcontroller board called Arduino UNO (see Figure 2 below). Since its release, it enabled worldwide design enthusiasts to create all sorts of interactive objects and responsive environments (Kolarevic, 2014). In doing this, digital receptors, maturity in BIM technology with visual programmable geometry sparked imagination to reignite the vision of responsive facades (Kensek, 2014).

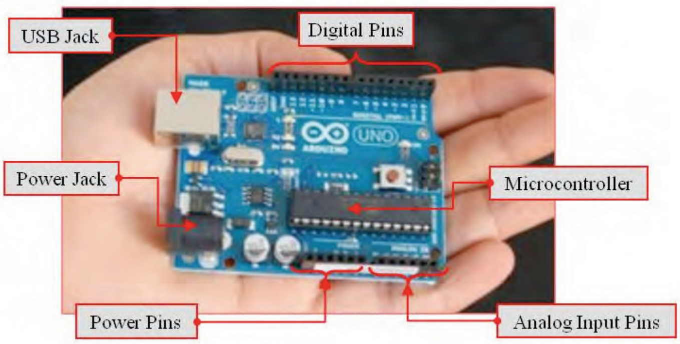


Figure 2. The Arduino UNO microprocessor board (source www.sciencebuddies.org).

2.1. CREATING AND MAKING LOW-COST PROTTYPES

There are many references made to similar research attempts in dynamic façade using programming scripts, DDC and the hardware automation process. Especially in (Kensek, 2014) who attempted to evaluate in eight case studies to connect simple BIM model, Arduino and environmental sensors to control sunshade 3D model. In the examples, a movable light-shelf was adjusted using Rhino and Grasshopper with Aruino, in support from DIVA daylight analysis. In addition, other examples utilized Revit and Dynamo as link between the 3D model and Arduino to control the model parameters. Regardless of the several attempts, our approach in particular explores three important aspects:

- How the physical model objects and digital geometry are synchronized 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 the response in the prototype because it plays a major role in creating an effective a kinetic system.

As we begin exploring this approach, our small dynamic façade prototype experiment re-visits the dataflow and processing of a responsive dynamic facade. As discussed by Sharaidin (2014), this is mainly because static facades totally contrast from designing dynamic facades, which involves various configurations. It is in this context that “Creating and Making” approach and convergence of dataflow into the early design phase requires careful representation and change to the designer mindset to achieve high quality end product (figure 3). Furthermore, there is a need to investigate how effective DDC tools links with the kinetic facade mechanism. As a consequence, the process of implementing DDC optimization for dynamic facades is underdeveloped and requires further testing and evaluation.

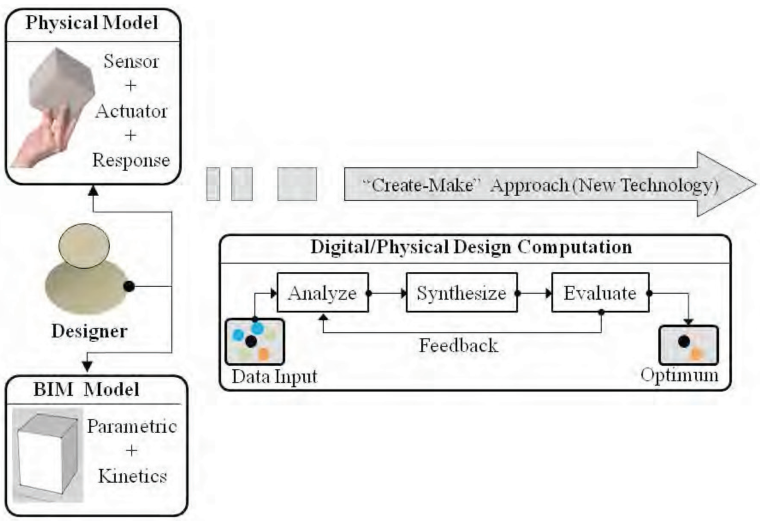


Figure 3. A Create-Make mindset approach and discovery process.

3. Physical/Digital Façade Experiment Framework

Our experimental prototype is of a small façade and assumed to be automated with a dynamic self-updating-loop data flow. 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 (figure 4). In Phase (2), the real small prototype components dynamically change according to sensor solar exposure values which "Self-Update" the digital façade panel.

As far as movement of dataflow in kinetic facade, this prototype expands BIM working environment while taking into considerations facade geometrical properties like: panel shape and panel size to reflect the feature of the intended design. We created a digital-hardware-physical computation framework between the prototype parts and set of dataflow involved in the kinetic movements. As shown in the figure 4 below, this experiment is an exploration of a new approach to implement our proposed "Self-Updating" BIM model for effective analytical design process of responsive facades reacting to variety of conditions (e.g. solar exposure, function, and aesthetics)

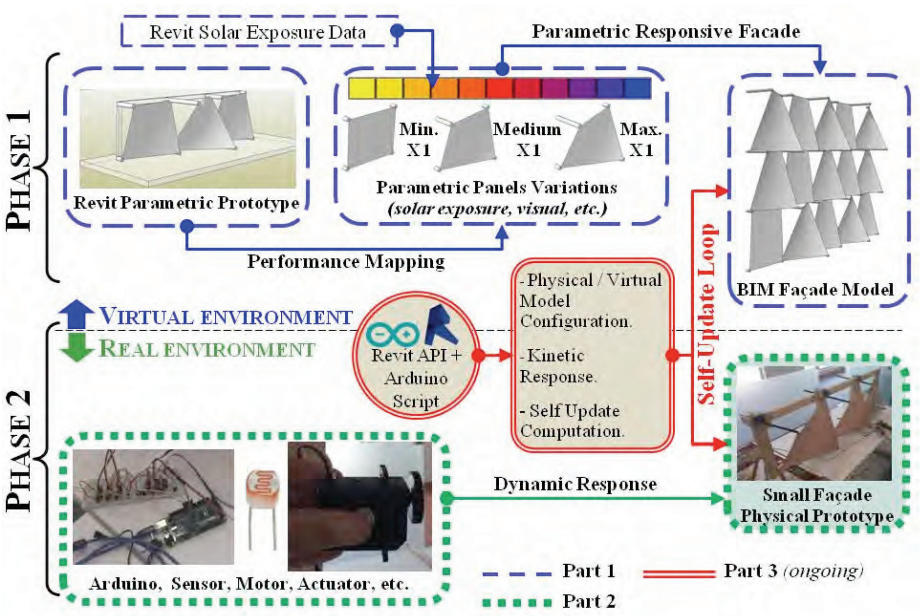


Figure 4. Proposed research framework self-updating.

3.1. THE SMALL PROTOTYPE PARTS

Over the course of developing the conceptual framework shown in figure 4 above, we realized the difficulty of installing an actual scale 1:1 prototype on the entire building façade. The data and development framework intersects within four parts as visual expression is resulted from user input and simulated environment. The four parts described below is intended to follow a typical “Creating-Making” design process while simulating a wide variety of technical challenges that may present themselves in everyday practice.

3.1.1. PART (1) – Parametric Façade Panels Utility

This part utilizes Revit ® BIM parametric modeling to construct 3D façade panels prototype. The core concept in parametric modeling is that objects and sub-objects are associated with one another thru parametric rules keeping their association as one framework. Single change to one parameter would affect the panel properties.

The panels are assigned an “X1” parameters to control the stretch/retract distance, and hence panel opening area (figure 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 color-range values from the solar analysis, the three façade configurations produced are:

[**Small Opening Size =** High Exposure = Yellow Color = Minimum X1].

[**Medium Opening Size =** Medium Exposure = Red Color = Half X1].

[**Large Opening Size =** Low Exposure = Blue Color = Maximum X1].

And so on, the opening size is determined by 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 of made of pixels whereby each pixel Red Green Blue (RGB) values can be obtained to evaluate solar exposure range values. These RGB values of a solar exposure image were implemented using C# programming language available in the Revit API.

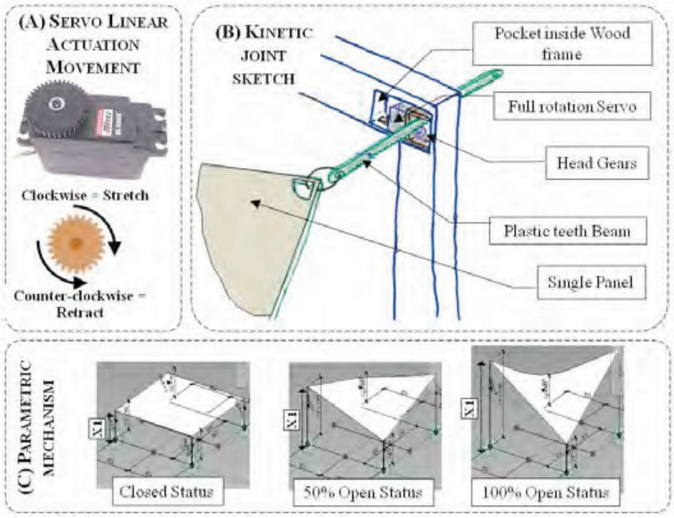
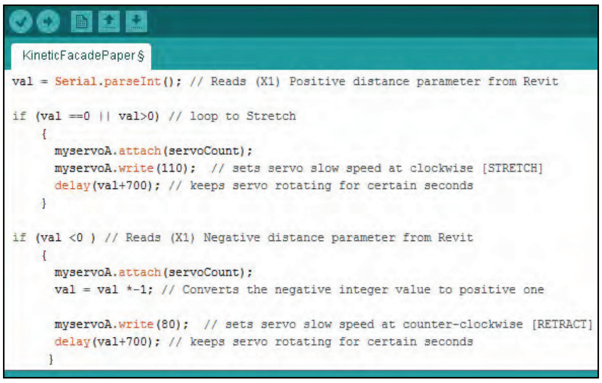


Figure 5. Sketch of the joint assembly idea with the motorized actuation parts.

3.1.1. PART (2) – Physical Façade Prototype Assembly

A sketch illustration of the physical prototype parts is shown in figure (5, b) below. It is constructed from affordable materials suitable for experimenting with responsive facade design. The materials such as wood support frame and flexible low-cost tensile fabric are adapted in the prototype to mimic the structural/mechanical system. The stretch/retract motion mechanism consist of motorized 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 "Self-Updating-Loop" responsive façade feature. The clockwise/counter-clockwise movement of the kinetic panel was based on an actuation mechanism by rolling gear beam attached to full-rotation servo motors (See figure 5, a). Through exploration while constructing 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.




```
val = Serial.parseInt(); // Reads (X1) Positive distance parameter from Revit

if (val ==0 || val>0) // loop to Stretch
    {
      myservoA.attach(servoCount);
      myservoA.write(110);  // sets servo slow speed at clockwise [STRETCH]
      delay(val+700); // keeps servo rotating for certain seconds
    }

if (val <0 ) // Reads (X1) Negative distance parameter from Revit
    {
      myservoA.attach(servoCount);
      val = val *-1; // Converts the negative integer value to positive one

      myservoA.write(80);  // sets servo slow speed at counter-clockwise [RETRACT]
      delay(val+700); // keeps servo rotating for certain seconds
     }
```

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

Each façade panel is controlled by two full-rotation servos and in turn each servo is identified by the Arduino programmable board thru digital pins. Every pin represents a channel of communication between the computer ports where input information is sent to the servos 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 Aduino programming script translates an electrical pulse delay to control the continuity of rotation and speed of servos. We experimented with this delay thru trial and errors to figure out the conversion of rotation cycles to translate to certain 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 speeds rotations.

3.1.1. 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 and also a simple C# Graphical User Interface (GUI) in Revit API that accepts actions made by users. As mentioned previously in this paper, currently we are only discussing phase one of this on-ongoing research which is the kinetic system from Digital to Physical. This will be discussed in the following while describing the data-flow process.

- ***Arduino Script:*** evaluates two possible scenarios for a positive or negative (X1) parametric integer values sent from Revit to Arduino via USB serial communication port connected to the computer. This connection is the key part in this study of sending/receiving data between the Revit BIM prototype and the physical one. The general structure of the script is shown in the figure 6 above where the control occurs for actuation direction, speed of actuation and assigned servo motor pin number. 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 after the following one sequentially and not at the same time as. This development realized such drawback issue due to the maximum voltage required to supply each servo motor.

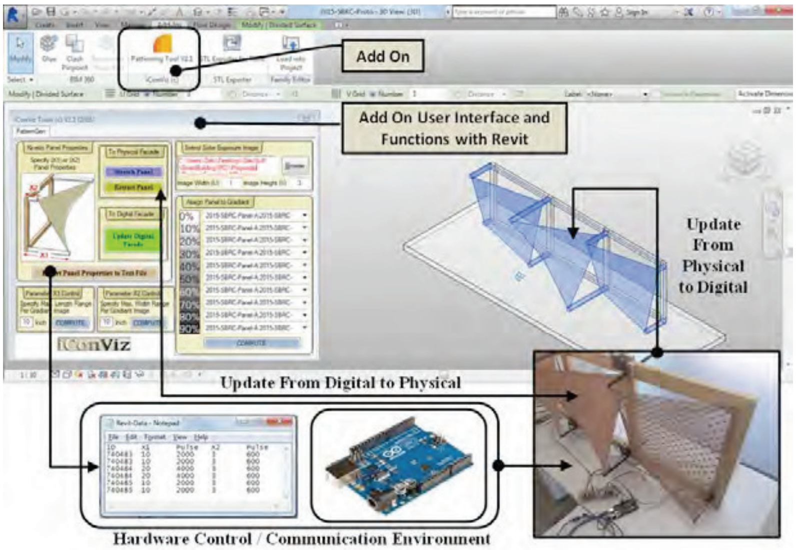


Figure 7. The Revit custom add-on and graphical user interface for kinetic façade.

- ***Custom Built Revit Add-On:*** designed in our work using the Revit API C# programming in order to achieve the translation from digital to physical (and the opposite). In terms of achieving the first phase of this research, it defines the behavior with logic to manipulate/read "X1" parametric panel input values. As illustrated in figure (7), the way of communicating the digital/physical façade properties is thru 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 occurred at different scenarios was real-time solar image exported from the Revit Solar Radiation add-on. The physical façade panel configuration is updated constantly using the custom add-on according to different solar radiation studies. As mentioned before, the physical prototype as controlled by the digital analog pulse sent for the custom add-on to Arduino board as a kinetic response for either increase/decrease of "X1" parameter.

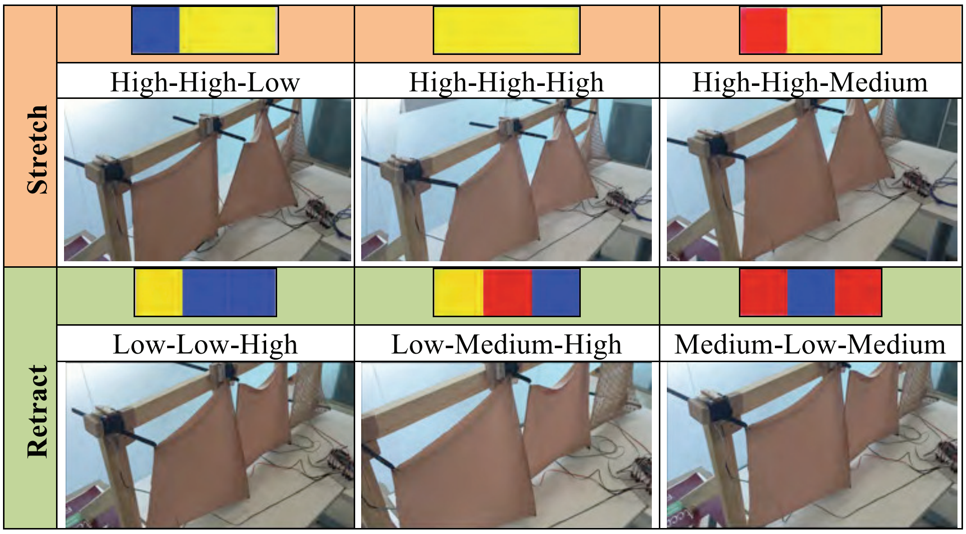


Figure 8. Small prototype parts and assessment of stretch/retract mechanism.

4. Preliminary Experiment Outcomes *(Digital to Physical)*

A series of six test-runs experiments have been initiated to illustrate the application and evaluate our proof-of-concept kinetic facade prototype during the early stage of façade design. Our aim is to simulate a real world environmental condition using simple solar exposure range values such as: low, medium and high. For each stretch/retract test-run, variations in the resulting façade panel movement were mapped from the digital to the physical based on input from four solar exposure analysis image. The resulting façade responsiveness was evaluated and compared in terms of: motor rotation movement, form/shape flexibility, and digital to physical design similarity. The test-runs outcome comparisons are shown in figure 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. The main aim, at this stage of the research, was to examine the efficiency and suitability of the kinetic mechanisms. The three assessments are shown in the table of Figure 8 and described below.

- **Assessment (1) – Motor Rotation Movement:** as the user initiated a stretch/retract action, the servo motors rotate according to needed directions (i.e. clockwise or counterclockwise) and in a uniform set of speed. The increase/decrease change in the size of the opening is updated slowly. There were some minor issues with a delay in movement of some servos in less than a second time which caused variation in the rotation speed. This issue is attributed to material-to-material friction interaction which affects the repetitive rotation movement. The servo motor achieved the necessary 360° rotation and in turns the tooth-beam actuates to enables the panel to attain a Low/Medium/High position. Allowing the users to change the speed of motor rotation was not 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:** is a major challenge in constructing kinetic façade prototype as it reacts to input/ data acquisition to create their flexible movement. The experiment led to permit the single panels movement of panels and thus allow for flexibility and interactive transformation. The tensile fabric-material utilized showed various responsive kinetic transformations for use in the kinetic façade. As the changing shape of the façade panels occurs, the panels demonstrated an elastic and flexible surface structure movement with few mechanical problems. Most importantly, the problem of friction during operating kinetic facade prototype is reduced as result of using the low-weight panel material and slow actuation speed reducing dependence on heavy mechanical components. Since facade responsiveness in this experiment needn't be in real time, it has been calibrated to respond in larger time scales like every hour at best. If high flexibility is needed then more electricity is necessary.

- **Assessment (3) – Digital to Physical Design Similarity:** through this exploration, we observed the visual similarities between a parametric façade model and behavior 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 similarity between digital and physical have a capacity to create matching facade patterns configuration. This effort on mapping 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 facade geometry for different purposes. In this way, designers can interact with the digital form of the façade geometry and the density of its pattern and obtain visual feedback. Also, one can use the resulting parametric model properties to validate the design with 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 facade in a different way than was previously possible. In doing so, we took advantage of the rich parametric information in a BIM facade model to understand the kinetic translation process to a physical facade prototype. For this purpose, this small project explored the principles and mechanism in the design workflow through a mixed digital-physical prototyping. Many practitioners and architecture educators consider "Creating-Making" a critical approach of 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 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 regards, 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 digital versus physical realm is that manually constructing prototypes are also necessary. The user interaction and sharing of digital information between software, hardware and kinetic building components is a whole challenging process that requires physical prototyping. The custom add-on was necessary to push the development of the experiment in kinetic architecture forward.

The presented experiment here is considered 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 a starting point of our efforts to develop a connection to the BIM model from the physical model.

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