Performance-Oriented Kinetic Façade Design Based on Interworking between Physical and Digital Models

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Abstract:
Kinetic façades, which respond to changing environmental conditions or user demands, require a design process different from that of traditional static building components. For performance-oriented design of kinetic façades with dynamic movements, interworking between the physical model and the digital model via physical computing is advantageous. Even though the digital model can control the actuators of the physical model in real-time, the two models cannot correspond with each other, due to physical conditions including material properties and the surrounding environment. For accurate evaluation performance, the shape and motion of the physical model needs to be reflected in the digital model. This study aimed to devise a motion-capture-based system of interworking between the physical and digital models. The motion-capture data of the physical model can be used for verification of the deviation between it and the digital model and, based on its shape, for optimization of Kinetic façade operation.

Keywords: Kinetic façades, Performance-oriented design, Optimization, Motion capture

1. INTRODUCTION
Façades play a key role in defining energy consumption, indoor environmental quality and building exteriors (Loonen, 2010). The environmental conditions surrounding façades change constantly from the viewpoints of urban development, culture, and climate. Conventional façades are static, and so cannot adapt to changes which are occurring at ever-higher frequencies in overcrowded cities. With regard to building performance improvement, one challenge is to explore the dynamics of architectural space by re-thinking the concept of architecture and going beyond conventional static, single-function spatial design (Pan & Jeng, 2008). Kinetic façades, for example, alter their function and shape according to user requirements and environmental conditions (Moloney, 2011). Kinetic façades can operate where embedded computation for intelligence and the physical counterpart for kinetics converge. Emerging development of Information and Communication Technology (ICT) is leading kinetic façades from a mechanical paradigm of adaptation to a biological paradigm (Fox & Kemp, 2009).

The traditional design methods for façades result in the best static mix of performance and aesthetics. The composition of static façades typically has been based on the interrelationships among components and the manner in which the components relate to the composition as a whole (Moloney, 2011). Kinetic façades’ performance is a function of geometric transformation (i.e. translation, rotation, scaling). In terms of performance, designers should consider the kinetic mechanism, material behavior and the kinetic pattern (Sharaidin, 2014). Kinetic façades, equipped with robotics, embedded systems, and sensor technology, are similar to complex machines. Kinetic façades cannot be designed successfully by the traditional design methods that are implemented after construction (Kim, 2015). There is a great demand for effective methods that can be used at the early design stage of kinetic façade systems, both within the Academy and in more practical contexts (Addington, 2005; Loonen, 2010; Moloney, 2011).

The physical and digital models have been widely utilized in the architectural design process as design media. When employed separately for kinetic façade design purposes, they have limitations; interworking between the two models, rather, is an effective medium for performance-oriented design. Physical computing makes it possible to bridge the gap between the models; furthermore, an open-source electronic platform such as Arduino or Raspberry pi helps designers and students build and test prototypes easily and quickly, even without an engineering background. Certainly, the development and dissemination of physical computing applications have accelerated the growth and expansion of interworking in the design of kinetic façades.

Geometric precision and physical force are the main elements affecting kinetic façade performance (J. Parkes et al., 2008). Although the actuators of the physical model can be controlled by the digital model in real-time, the shapes of the two models, digital and physical, cannot correspond with each other. The digital model’s parametric method can generate numerous forms based on geometrical accuracy, but the physical model’s shapes are transformed by physical conditions including material properties and physical behavior. Thus, the digital model can
contain a physics-based algorithm, but it cannot reflect the physical world perfectly; the exploration of the various alternatives during the early design stage, moreover, is prohibitively complex and difficult for designers (Sharaidin, 2014). For accurate performance evaluation then, the digital model must reflect the shape and motion of the physical model. The present research aimed to develop a system of interworking between the physical and digital models that reflects the shape of the physical model in performance-oriented design of kinetic façades.

2. RELATED WORK

2.1 Physical model and digital model

A designer devises a form for an object without having the actual object in front of him (Gänshirt, 2007). In the constant process of the negotiation of reality, a designer needs a medium that interlinks different disciplines in thus gradually approaching, from the abstract to the concrete, the desired outcome (Felix et al., 2009). Traditional physical models, termed “handmade,” “manual” or “material,” are made of clay, balsa wood, plastic, metal or other material. Such models are efficient for three-dimensional understanding of a structure, space or form. Digital models, deemed “electronic,” “computer-aided” or “virtual,” emerged with the integration of computers into architectural design. Digital models are better for design development, as they demand higher levels of geometrical definition and abstraction, thereby enabling the coordination and elaboration of details and complexity (Cheng, 1995). Multiple iterations of physical-digital modeling enhance the design process, especially in the early stages (Bermudez & King, 2000).

2.2 Performance-oriented design

Performance-oriented design is an approach to architecture by which building performance is a guiding design principle. Building performance can be defined very broadly, from financial, spatial, social and cultural perspectives to purely technical (i.e. structural, thermal, acoustic, etc.) ones. From the early design stage, multiple performances are considered simultaneously by close collaboration between the many parties involved (Kolarevic & Malkawi, 2005). Designers, using parametric models, can generate numerous alternatives while maintaining design intents. Simulation and optimization with digital models support the form-finding process, which helps designers choose the best alternative.

2.3 Interworking between physical model and digital model

Simulation speeds up the design process, increasing efficiency and enabling the comparison of a broader range of design variants, leading to more optimal designs (Loukissas, 2012). Furthermore, digital models support designers’ decision making with a wealth of information derived from Building Information Modeling (BIM). However, since the end goal of the design process is to install and operate kinetic façades, the ability to understand the connection between the digital design process and its physical actualization is crucial (Zarzycki, 2014). Indeed, the physicality of architecture demands some direct reference to the physical world (Bermudez & King, 2000). In other words, the motion of kinetic façades, as simulated on digital models, should be tested on physical models, too. Physical prototyping allows the designer to have direct engagement with the material properties and behaviors, which are hardly visible in the early design stage (Sharaidin & Salim, 2012). Even though media iterations help designers grasp the differences between media and lead to maximal exploitation of their capabilities (Johnson, 1997), the synergistic potentials of the physical and digital environments cannot be derived simultaneously. Alternatively, interworking between the physical and digital models can function as a hybrid medium in kinetic façade design. Interworking reduces the time consumption incurred due to digital models’ complexity (Sharaidin, 2014) as well as the effort necessary for physical models’ transformation and manipulation (Bermudez & King, 2000). Physical computing, consisting of a sensor, processor, and actuators, enables physical-digital model dialogue by which the designer can gain feedback from both in real time (Peter, 2013).

2.4 Motion capture in kinetic façades

In the architecture and building construction fields, technology digitizing the shapes of physical objects has been researched extensively. Components’ geometrical variation from their planned versions during the process of construction is inevitable. 3D laser-scanning technology, for example, provides 3D as-built models to an accuracy of 1mm (Stone & Cheok, 2001), and is becoming even more important as it is united with other technologies such as BIM, Global positioning systems (GPS), and drones. This technology, however, is inappropriate for physical scale models in the design process, owing to its significant expense and inability to capture moving objects’ X, Y and Z coordinates. Another approach, one especially suitable to the process of kinetic façade design, is needed: motion capture.

Motion capture is the process of recording the movement of objects or people. It is used in military, entertainment, sports, medical applications, among others. There are two approaches to the motion capture of a performer: marker-
based and makerless. The marker-based approach identifies markers attached to the performer, and tracks its motion according to the positions or angles between the markers. The markerless approach extracts the silhouette of the performer from the background. Both approaches to motion capture require a special environment and multiple cameras. In recent years, several new markerless motion-capture approaches involving simpler and cheaper equipment have been introduced (Hasler et al, 2009). With the advent of Microsoft Kinect in 2010, motion capturing based on depth data has become more feasible, allowing for a consumer-grade and depth-based single-camera motion-capture system (Shotton et al. 2013). Although Kinect was developed for the Xbox 360 video game console, it is accurate enough to be used for reverse engineering.

In its application to responsive architecture including kinetic façades, Kinect is typically used as a sensor for detecting objects to which kinetic façades will respond. In other words, Kinect is rarely used to reflect the shapes of kinetic façades in terms of reverse engineering. In previous research by Jang et al. (2013), Kinect was used not only for tracking hand movement mimicking the Sun’s orbit but also for representing the motion of a physical façade model (Jang et al., 2013). The represented model, however, is not used for performance-oriented design of kinetic façades. Brennan et al. (2013) introduced a Grasshopper add-on (Quokka) that allows the use of Kinect in Rhino3D. Without the need for calibration or unfamiliar coding, both students and practicing architects can utilize Kinect for a number of experimental/pedagogical applications in architecture including performance, interactive design, collaborative design, 3D scanning, real-time data capture and shape-design recognition, shape assessment, and feedback design (Brennan et al., 2013).

3. RESEARCH DESIGN

3.1 Variables and kinetic objects

Designing kinetic façades entails a series of processes for determination of variables in terms of parametric design. The variables of kinetic façades can be divided into two groups: variables of non-movement and variables of movement. Variables of non-movement are fixed after the design process. Variables of movement are constantly being changed while kinetic façades operate after construction. Variables of non-movement are, for instance, the number and size of panels, whereas two examples of variables of movement are the rotating angle and speed of servo motors. If variables of non-movement are not determined, the optimization process results in unrealistic outputs. Thus, one of the main focuses of the present research was the process of variables-of-movement optimization or form-finding after determination of the variables of non-movement.

The form of kinetic façades affects the performance of space. This research dealt with three kinetic objects as different forms of kinetic façade: a physical object, a digital design object, and a digitized object. A physical object is a kinetic object of a physical model. A digital design object and a digitized object are both kinetic objects of a digital model; but whereas a digital design object is based on geometrical principles without physics, a digitized object is based on the geometry of a physical object.

3.2 Hypotheses

This research’s proposed interworking between physical and digital models was performed in order to verify the following two hypotheses.

(1) The 3D shape deviation between a physical object and a digital design object can be measured in the digital model. Such deviation cannot be measured in the physical environment but only in the digital environment. Via motion capture and manipulation, a physical object can be regenerated as a digitized object in the digital model.

(2) The optimization results of a digitized object and a digital design object do not correspond with each other. Performance is a function of the shape of a kinetic object of a kinetic façade. Correspondingly, a digitized object demonstrates performances closer to reality than can a digital design object, because a digitized object reflects a physical object as transformed by physical conditions.

3.3 Framework of Interworking between physical and digital models for kinetic façades

Interworking involves motion capture for performance-oriented design based on a physical object. As shown in Figure 1, the respective components of the physical and digital model match each other. For recursive optimization, the data flow between the components is cyclical. A kinetic object affects the performance of space through geometrical transformation. A physical object is a counterpart of a digital design object or a digitized object. A room model is essential for measuring the performance of space in both models physical and digital. Physical computing, which bridges the gap between the physical and digital models, consists of a processor, actuators, and sensors including a motion sensor. A processor connects digital model input with the actuators in the physical model. It converts the digital model’s digital signals to analogue signals and vice-versa. In turn, it transmits the physical
model’s sensor values to the digital model. A motion sensor transmits the geometrical transformation to the digital model, wherein a digitized object is generated for the purposes of performance-oriented design.

3.4 Optimization process

Figure 1 can be rearranged into Figure 2 while maintaining the data flow sequence and explained from the viewpoint of “Computer-aided appraisal.” This optimization process follows the ‘Generation–Measurement–Evaluation–Modification’ (Maver, 1980) sequence during the form-finding process.

(Generation) Generation starts with input of the variables of motion into the digital model. In the case of optimization only of the digital model, the inputs control a digital design object directly and a digitized object indirectly. The inputs control the actuators of the physical model via the processor. The data flow bifurcates upon the motion of a physical object: that of the physical object and that of the digitized object.

(Measurement) A physical object affects a room model of the physical model. A digitized object affects a room model of the digital model. Each model measures its own performance. The physical model obtains performance data via sensors, whereas the digital model acquires it via an analysis program related to structure, energy, costs, and so on.

(Evaluation) The digital model integrates, evaluates, and visualizes the performances measured in both models.

(Modification) The variables of motion are modified according to the theory of optimization, and the optimization process repeats.

4. EXPERIMENTAL ENVIRONMENT

4.1 Twisting Louvers

The performance-oriented design of the proposed kinetic façade was conducted by interworking as outlined in the preceding section 3. Given that the solar angle is always changing, it is difficult to maintain interior illuminance evenly with static louvers. To overcome the limitation, Twisting Louvers control entering sunlight by reacting to such changes. Twisting Louvers are attached outside the curtain wall and transformed by the two servo motors installed one each at their top and bottom. A servo motor, with its rotation range of ~180 degrees, makes various openings between the Twisting Louvers to optimize the light-input pattern. Light sensors arrayed uniformly on the floor measure the interior illuminance in real-time. A processor obtains the illuminance data from the light sensors and determines whether the illuminance requirement is satisfied or not. If it is darker than the proper illuminance, a processor controls the servo motors to make it brighter.
4.2 Physical model and physical computing

As shown in Figure 3, the physical model consists of a 1:10-scale model and a 1:5-scale model interworked with the digital model. The physical computing bridging the digital and physical models consists of a micro-controller (Arduino mega 2560) and a motion sensor (Microsoft Kinect).

The 1:10-scale model consists of five Twisting Louvers and a room model. Each Twisting Louver is made of folded paper and 2 servo motors. A room model has a length of 3 meters, a width of 4 meters, and a height of 3.3 meters, and is equipped with 16 light sensors arrayed uniformly. The number of light sensors is restricted by the number of analogue pins of Arduino mega 2560. On a 1:10-scale model with a desk lamp, designers can test the motion and effect of Twisting Louvers indoors. However, a 1:10-scale model is inappropriate for motion capture, as Kinect cannot generate an intact point cloud from the surface of a Twisting Louver surrounded by other components.

A 1:5-scale model is not equipped with a room model or any light sensors for motion capture. On a 1:5-scale model therefore, the folded paper of the 1:10-scale model is replaced by triangle panels and hinges made of ABS (acrylonitrile-butadiene-styrene resin) fabricated by an FDM (Fused Deposition Modeling) 3D printer for accuracy. A 1:5-scale model takes concerted action with a 1:10-scale model simultaneously.

Intense sunlight with its powerful infrared rays blinds the Kinect infrared sensor, thus causing interference. Kinect has a tolerance of plus or minus 1 centimeter within a 1 m – 3 m range in indoor conditions (El-laithy et al., 2012). Thus, a series of experiments was conducted indoors with the distance between Kinect and a 1:5-scale model set at 1.5 meters.

4.3 Digital model

The main 3D program of digital modeling is Rhino 3D, the algorithmic modeling plug-in for which is Grasshopper. The 3D objects in the digital model are the Twisting Louvers and the room model. The Twisting Louvers exist as both a digital design object and a digitized object. Although it cannot reflect on the physical condition, the digital model, due to its geometrical accuracy and parametric method, is efficient in determining the variables of non-movements. A digital design object provides a 3D printer with geometrical data. A digitized object reflects a physical object as transformed by physical conditions such as material properties. A physical louver should be faced with Kinect for intact motion capture, so that a point cloud can be generated evenly on the surface of a 1:5-scale model. A point cloud is a set of points that exist in three dimensions. Every point is defined by three coordinates, X, Y, and Z, and displays color data. A point cloud from Kinect is converted to a mesh by Delaunay triangulation in the digital model. A mesh functions as a digitized object that can be utilized in performance analysis.
5. EXPERIMENTAL FINDINGS

5.1 Shape deviation between digitized object and digital design object

The shape of a physical object is formed by the angles of the respective servo motors. The gap between the angles of the upper and lower servo motors is a maximum of 160 degrees. In the digital model, a digitized object is overlapped onto a digital design object, and the shape deviation between them can then be measured and visualized. Table 1 lists each of the angles of the servo motors and the corresponding maximum deviations between a digital design object and a digitized object. When the angles of the servo motors are parallel, the bottom of the physical object is loose due to its self-weight. As the gap between angles becomes larger, a physical object becomes tighter and the maximum deviation grows.

<table>
<thead>
<tr>
<th>Upper angle(˚)</th>
<th>ALT1</th>
<th>ALT2</th>
<th>ALT3</th>
<th>ALT4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower angle(˚)</td>
<td>0</td>
<td>40</td>
<td>80</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 1. Shape deviation between digitized object and digital design object

![Digital Model - Top view(top) - Axono view(bottom)]

Max Deviation (mm) | 19.21 | 21.33 | 28.23 | 32.75

5.2 Optimization results of design object and digitized object

The objective of Twisting Louvers optimization is form-finding of time-based motion satisfying the optimum illuminance for offices: an average 400 lux. The angles of servo motors function as the optimization input. The present illuminance analysis was conducted by DIVA (Grasshopper add-on) based on EnergyPlus. The optimization process was conducted by Galapagos (a Grasshopper-based component) based on the Genetic Algorithm. Sixteen (16) illuminance values measured by the 16 light sensors of the physical model were referenced in order to set up the digital model but not used as performance measures in the optimization process. The digital model is more accurate and specific than the physical model, because the simulation on the digital model is conducted on the basis of real location and weather data. The optimization process is conducted with weather data collected in Incheon, Korea, under conditions of clear sky and sun. The optimization process was conducted at 3 hour intervals on 21st June, 2015 (the summer solstice).

In the form-finding process, the optimization result of a digital design object has two roles. One is to be compared with the optimization result of a digitized object. The other is to narrow down the input range of a digitized object with efficiency and accuracy. If a servo’s range of motion is set from 0 to 180 degrees in the optimization process for a digitized object, a physical object should be facing Kinect every time the servo motors rotate. However, frequent location adjustments degrade the accuracy of motion capture as well as the automation of the optimization process. Thus, the servo range of motion was restricted to within plus or minus 10 degrees of the optimization result of a digital design object for stable motion capture with a fixed 1:5-scale model.

As shown in Table 2, the optimization results for a kinetic object include the servo motors’ angles and average, maximum and minimum illuminances. The specific values under the same conditions differed from each other. The deviations of the servo motors’ angles ranged from 1 to 5 degrees. The deviations of average illuminance ranged from 2 to 75 lux. There was a large difference in the optimization result at 12:00, which was close to the culmination time. The ranges of the digitized object from the minimum to the maximum were wider than those of the digital design object.
Table 2. Optimization results of digital design object and digitized object

<table>
<thead>
<tr>
<th>TIME</th>
<th>9:00</th>
<th>12:00</th>
<th>15:00</th>
<th>18:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>Digital</td>
<td>Digitized</td>
<td>Digital</td>
<td>Digitized</td>
</tr>
<tr>
<td>Upper angle(°)</td>
<td>142</td>
<td>139</td>
<td>69</td>
<td>71</td>
</tr>
<tr>
<td>Lower angle(°)</td>
<td>61</td>
<td>57</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>Average (Lx)</td>
<td>304.83</td>
<td>313.20</td>
<td>355.26</td>
<td>430.06</td>
</tr>
<tr>
<td>min (Lx)</td>
<td>max (Lx)</td>
<td>191</td>
<td>618</td>
<td>190</td>
</tr>
</tbody>
</table>

6. DISCUSSION

6.1 Verification of hypotheses

The 3D shape deviation between a digital design object and a digitized object can be measured in the digital environment. The optimization results of a digitized object and a digital design object do not correspond with each other in terms of shape or performance. The closer to the culmination time the measured time gets, the larger the deviation between the optimization results becomes. That is why the shape of the kinetic facade affects the interior illumination more when the intensity of illumination is high. The average illumination of a digitized object at 12:00 is in excess of 400 lux, and so occupants can work without artificial lighting. A digitized object is closer to the real construction than is a digital design object, because it reflects the transformation due to physical conditions such as self-weight and material properties. In other words, a digitized object provides designers with more accurate performance data than can a digital design object. However, that does not mean that a digital design object is useless. Rather, the optimization results for a digital design object help those for a digitized object with a single motion sensor by saving time and increasing accuracy.

6.2 Practical application

The method can work well even in practical environments where typically designers’ decision-making depends on time and money. First, the method helps practitioners conduct performance-oriented design of kinetic façades more efficiently from the early design stage. Nowadays hardware and software related to physical computing are becoming cheaper, faster, and easier (Max & Fox, 2011), and so architects or students who are unfamiliar with ICT can still construct and test a prototype of kinetic façades both physically and digitally. Second, the method helps architects research the physical behavior of a kinetic façade. Kinetic façades can exploit the structural potential of material using elastic deformation, the so-called bending-active structure (Lienhard & Knippers, 2015). The method therefore can function as a powerful medium for collaboration between architects and engineers. In fact utilizing this method, architects can propose economic alternatives that could not be realized by conventional materials or façades systems. However, this method cannot be applied throughout the whole design process of kinetic façades. As the process progresses, the design is required to be tested on a more realistic scaled model. Material properties of a miniature is different to a 1:1 scale mock up, thus this method can only have limited use by the architect when exploring conceptual alternatives.

7. CONCLUSION AND FUTURE WORKS

This research proposes a system of interworking between the physical and digital models that reflects the shape of the physical model in performance-oriented kinetic façade design. With Microsoft Kinect, a series of experiments were conducted to measure the shape deviation and to derive the optimization process using a digitized object. The method helps designers conduct performance-oriented design on physical models in place of complex simulation on digital models at the early design stage. The optimization process is suitable not only for academic applications but also practical ones wherein economy is a significant consideration with respect to both the design process and the design results.
The limitation of motion capture with a single Kinect is that the physical object has to be facing Kinect. Although a shape like a surface allows for motion capture with a single camera in the case of Twisting Louvers, more complicated 3D shapes with dynamic movements need multiple cameras and the multiple point cloud calibration process.

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REFERENCES


