Collaborative Responsive Façade Design Using Sensor and Actuator Network

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Abstract. The building facade interacts with its neighboring environment as an active element; therefore it is unreasonable to conceive the facade as merely a dividing entity between the interior and the exterior. The envelope system of smart building can dynamically improve dwelling conditions by intelligently reacting to climate changes. This research proposes a collaborative responsive building façade design method using sensor and actuator network. By synchronizing both virtual and physical models, the design state of the change or improve simultaneously. This study reflects the lighting level data among the various environmental elements to design responsive façade prototype. We utilized motion sensors to detect the movement of designer's gestures for creating more intuitive design process.

Keywords: Responsive Façade, Collaborative Design, Kinetics, Interactive Wall, Physical Computing.

1 Background

Modern buildings are heavily dependent on the use of mechanical equipment to maintain the comfortable indoor environment. This inevitably results in an increase of energy consumption. The building envelope has played a major role in manipulating indoor environment condition such as movement of heat, light, air, noise, and the indoor environment load (Lechner 2007). From this perspective, environmentally responsive approach to building design is important and intelligent skin systems have been actively developed nowadays. The envelope system of smart building can dynamically improve dwelling conditions by intelligently reacting to environmental changes. The building facade interacts with its neighboring context as an active element (Rafael 2010); therefore it is unreasonable to conceive the facade as merely a dividing entity between the interior and the exterior. Brand new technologies such as wireless sensor networks (WSNs) composed of sensors and actuators, which are mentioned as the Internet of Things (IoTs) have been merged into building systems. For example, sensory modules which are installed on the building skin can detect external environmental changes and actuators can make it react based on procedural routines (Lee and Yoo 2012). IoTs behave even more intelligently to cope with complicated

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constraints. In short, the responsive façade can function by the help of mechanical system, working with various sensors, actuators, and computer programming. By actively reacting to environmental changes, building skin can significantly improve the comfort of the dwellers and minimize energy consumption in a real-time manner. Also, it is possible to improve the overall building performance.

Responsive façade needs to be designed in different ways because it behaves like mechanical products in comparison with most conventional building system. Therefore if both physical and virtual models function complementarily with each other, designers may better concentrate on their design activities and enhance productivity as a result. This research is a follow-up of the previous study (Yi *et al.* 2012), which proposed an inter-dependent design method between one physical model and one virtual model. There are limitations in the previous study as followings; motion range of facade modules is limited to the simple horizontal direction, it focused on the basic interaction between the virtual model and the physical model, and sophistication lacks because simultaneous reflection of multiple environmental factors was not possible. To overcome these limitations, we propose a framework of cooperative design method in responsive façade design process. Motion sensors are used to detect the movement of both façade components and designer's gestures. The designer's gesture, in this case, can be replaced by the movement of the Sun. When the sensors capture unique features from moving objects, the system receives the data from the sensors and uses it for additional analyses.

2 Research Objectives

The aim of this research is to propose a collaborative responsive building façade design method using sensor and actuator network. This research places an emphasis on the advance of various virtual models by extending previously proposed system as shown in Fig. 1. Decision making process, in general, needs to consider various design factors which are required by many experts (Mueller 2011). On the basis of cooperation scheme with environment simulation models, the proposed system framework will help create rapid prototypes for multiple stakeholders. And it can improve the productivity of responsive façade simultaneously.

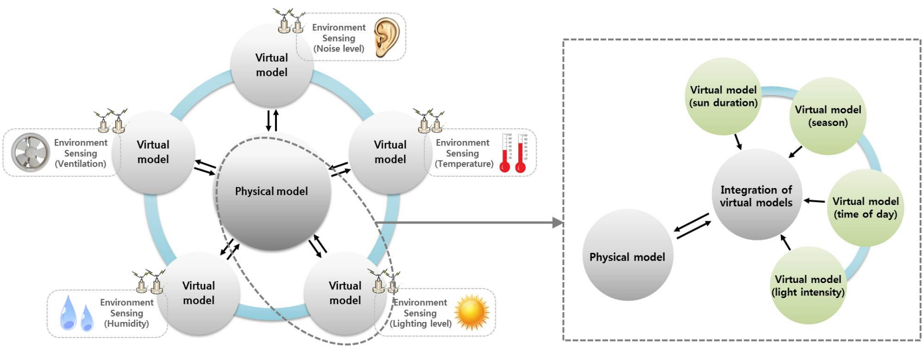

Fig. 1. The cooperative system of environmental elements

2.1 Needs of Interworking between Virtual and Physical Models

The design of responsive Facade should consider several important environmental factors (temperature, lighting levels, etc.) in the early design phase (Moloney 2006). Architects make physical models or virtual models to simulate the environmental properties. However, in the early design phase, virtual model of the ideal form and a physical model of the actual form are utilized independently, which makes design process more complicated (Redundancy and poor performance of analysis).

Physical modeling made of conventional materials such as cardboard has been one of the intuitively favorable methods to understand form, spatial depth, geometric properties, material properties, etc. Therefore, mock-up models have been utilized to figure out physical characteristics and architects made important evaluation by analyzing the physical model.

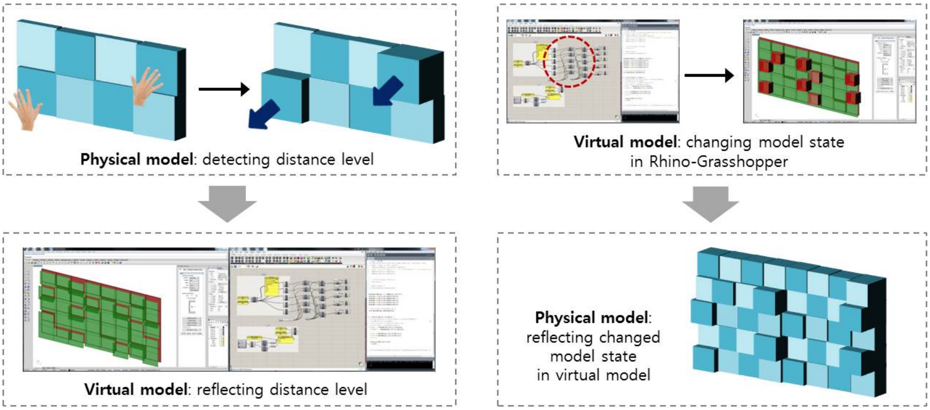

Fig. 2. Interworking between physical model and virtual model (Yi *et al.* 2012)

On the other hand, virtual models are used in all processes from the concept design phase to the construction phase, which are managed as digital data. For further details, it facilitates production automation, project management, structural analysis, thermal efficiency analysis, shape generation or shape-transforming by script, 3D modeling and visualization to construction engineers (Iwamoto 2009). The previous interworking model of Yi et al. (2012) is able to choose optimal architectural designs through two-way interaction between physical and virtual models (Fig. 2). In addition, alternation of element design in the virtual model could be reflected in the physical model by the help of wired data communication. This approach is of importance for the simulation of actual climate phenomena such as rainwater or outdoor wind in determining a detail and shape of intelligent skin (Kim 2012). Using this method, architects playing with these influencing factors of respective models can figure out the simulation results simultaneously and reflect those to their design tasks, and vice versa.

2.2 Scenarios for Using Daylight Data

Daylight is an important element for making sustainable building and is essential to decrease energy consumption (Ko *et al.* 2008). It is important to utilize natural light of indoor environment to increase the productivity and occupants' health (Hansen 2006). This study focused on the lighting level data among the various environmental elements to design responsive façade prototype. It is necessary for the effect of lighting level to be interrelated with virtual simulation and physical model in order to test according to geographical situation and context. To make inner space of a building comfortable and to maximize the aesthetic quality of a building façade by following programmed rules, each element constituting the building façade prototype can react according to the level of sunlight intensity by actively transforming its form. According to changing daylight, the performance of skin could be simulated in a virtual model and its result is reflected on physical model. The dynamic behavior of architect and façade could be re-applied to the virtual model as well. Unlike conventional façade shape, studies on various formal representations which can be systematically operated with the help of sensor and actuator network are conducted by designers.

3 Research Pipeline

This research proposes a system of cooperative design method focusing on responsive façade design as shown Fig. 3. Proposed framework could be divided into four major parts. Through this system, physical and virtual model can work to input and output concurrently.

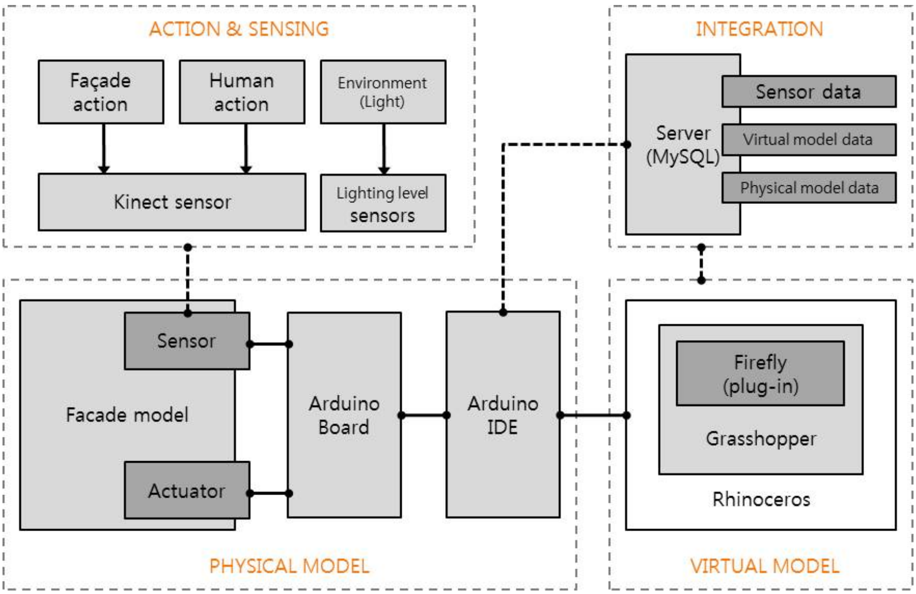

Fig. 3. The system of framework

In the action & sensing section, through installed lighting level sensors, each module receives sunlight intensity data. And motion recognition sensor detects both movement of façade and designer's gesture. Kinect™ of Microsoft™ are used as the motion recognition sensor. Kinect sensor receives depth data from infrared (IR) light. These sensors can measure the distance to the front objects in the range of 0.4 ~ 3m depth. The received depth information can be used for tracking or detecting surrounding objects and gathered data can be processed to comprehend human's pose and gesture selectively. Utilization of Kinect sensor based on NUI (Natural User Interface) makes it possible to detect nearby user's motion precisely. The data obtained by sensors are stored in sensor data server. In the physical model section, the prototype model represents actual movement by installed actuators in the facade model. Actuators reflect the virtual model data through Arduino™ IDE which connects with Arduino board. In the virtual model section, experts model 3D configuration using Grasshopper plug-in of Rhinoceros™ software. Firefly program was used to connect the system with the Grasshopper™. It is possible to connect Grasshopper™ with Arduino™ and Kinect sensor directly without extra coding process using UDP. In the Integration section, for systemic data management, virtual model data, physical model data and sensor data are saved in the MySQL™ platform.

4 Prototype Overview

This framework system focused on the physical facade model to make a prototype (Fig. 4). Each unit of the physical façade model connects with one servo motor and one lighting level sensor each. The behavior of the façade elements are detected by Kinect sensor and synchronized with the virtual model. The units perform a role in integrating between environmental sensor data and physical form to formulate combined conceptual design result in the early design phase. Architect will be assisted to support their decision making through this integrated model because the model system could confirm how well various elements are controlled simultaneously.

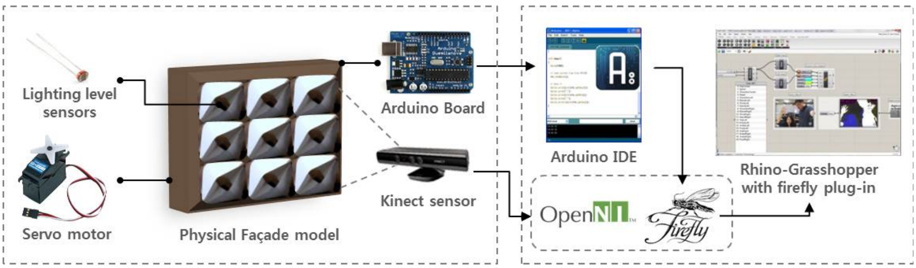

Fig. 4. The framework for the responsive façade design

4.1 Prototype Unit Development

The design idea of the unit is to observe light filtered through slits on the side as shown in Figure 5. Light pass into the inner side straight or overshadowed by broadening its gap. The effectiveness of solar shading could be differentiated depending on angle, size, and direction. These elements work as parameters for shading. For example, the points on a diagonal line of a square are parameterized to track the sun as shown in Figure 6. So the façade model can control the inlet of sunlight by transforming its physical properties. We made concept unit model using thick paper materials for easy crafting and work out a way to folding structure.

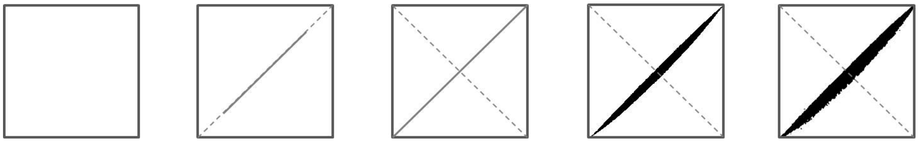

Fig. 5. The design idea for façade unit

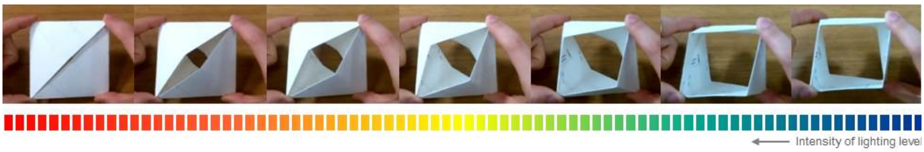

Fig. 6. Conceptual idea for unit opening by lighting direction: Sequential pictures

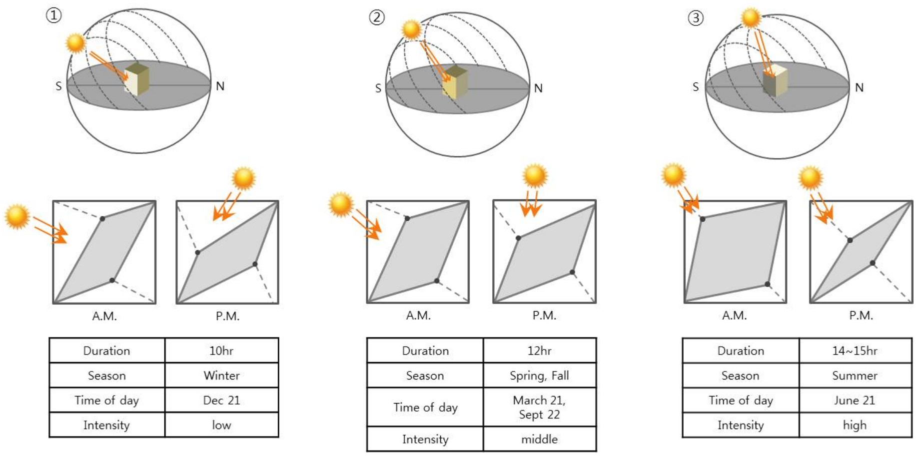

Fig. 7. Movement of the Sun and its effect on façade's state

Defined by the path of the Sun' diurnal motion, the height of the Sun and the duration of the day have influence on the seasonal building performance. The Sun's duration and intensity are most critical factors to understand for deciding the façade states. Figure 7 schematically represents the façade's behavior according to the Sun's movement. Those images from the left represent "the winter solstice", "the vernal and the autumn equinox", and "the summer solstice" that show the façade's reaction to the Sun.

4.2 Motion Data Working with Façade Prototype

In this proposed process, Kinect sensor plays a double role in detecting. First, Kinect™ detect human's gesture shown as shown in figure 8. When a designer decides angles of movement, human gesture could be used as input data. Kinect sensor allows that designer to be a controller themselves. Human gestural inputs are more intuitionally utilized for application the sun's movement. Because of this design process has limitations to control the light, a position of human hands replaces that of the sun. Thus, Kinect sensor is used to calculate the vectors of hands mimicking the sun. Also the gestural input reflects virtual model. And by employing Firefly plug-in, Kinect™ could be connected to Grasshopper™ and even Arduino™.

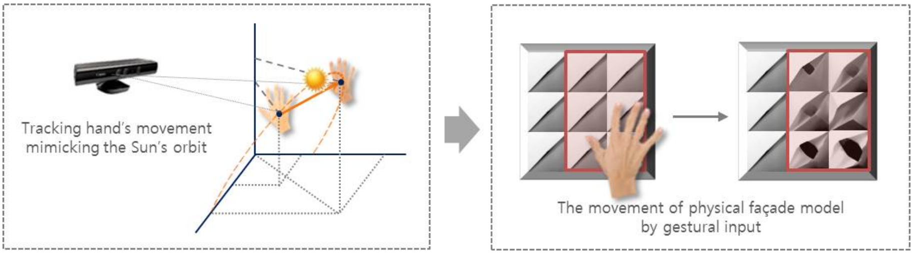

Fig. 8. Detecting human gestural input

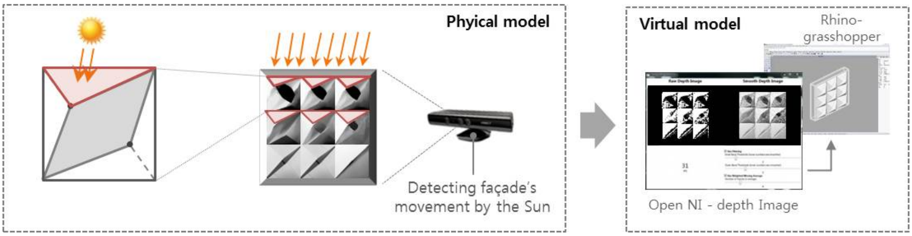

Fig. 9. Detecting physical facade movement

Second, the movement of physical façade model could be presented in Rhino Grasshopper™ as shown in figure 9. Kinect™ can detect movement of physical model and extract depth data and transmit the data to the computer. The transferred data will be applied to the virtual model in Rhinoceros™ platform as well.

5 Outlook

In this research, we propose a system framework to support cooperative design of responsive building facade based on multi-dimensional interactivity. By referencing previous research by Yi *et al.* (2012), several virtual models are interlinked and expanded to correspond to dynamic design constraints. Using this collaborative design system, design feasibility and productivity from rapid decision making can enhance the quality of a design process. Design process become more dynamic so that a real-time feedback is possible through interworking between a physical model and a virtual model, which was hardly shown in conventional architectural design methods. This research has still many limitations. As lighting was the only element to analyze in this prototypic research, we need to conduct a follow-up research which considers other environmental elements. And if rapid prototyping technologies were applied in more detailed manner, it would be possible to go beyond conceptual form. By adapting kinetic elements to physical model of facade skin, we can test aesthetic mobility of the shape. This can be effective when tracking the sunlight is interplayed with shading performance. This system framework can contribute to the design process for responsive facade design and for other architectural design which deal with kinetics as well. Rapid production of early design models can assist various stakeholders who are involved in a project by providing necessary information. And prompt design toolkit for novice designers can be developed targeting at similar design assignments.

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