Kinetic Façade Design Using 3D Scanning to Convert Physical Models into Digital Models

Do-Jin Jang, Sung-Ah Kim

Abstract—In designing a kinetic façade, it is hard for the designer to make digital models due to its complex geometry with motion. This paper aims to present a methodology of converting a point cloud of a physical model into a single digital model with a certain topology and motion. The method uses a Microsoft Kinect sensor, and color markers were defined and applied to three paper folding-inspired designs. Although the resulted digital model cannot represent the whole folding range of the physical model, the method supports the designer to conduct a performance-oriented design process with the rough physical model in the reduced folding range.

Keywords—Design media, kinetic façades, tangible user interface, 3D scanning.

I. INTRODUCTION

FAÇADES affect energy consumption, indoor environmental quality, and building exteriors [1]. The environmental conditions surrounding façades are changing from the viewpoints of urban development, culture, and climate. Conventional façades are static, so they cannot be adapted to the changes which are occurring at ever-higher frequencies in overcrowded cities. About building performance improvement, one challenge is to explore the dynamics of architectural space by rethinking the concept of architecture and going beyond conventional static, single-function spatial design [2].

A kinetic façade alters its function and shape according to user requirements and environmental conditions [3]. It consists of embedded computation for intelligence and physical counterparts for kinetics. For example, rotating louvers can optimize indoor environmental factors such as solar radiation and illuminance by reacting to the change in solar altitude throughout the seasons.

The traditional design methods for façades result in the best static mix of performance and aesthetics [3]. When it comes to designing a kinetic façade, the designer should consider kinetic mechanism, material behavior and kinetic pattern [4]. So, in both an academic and practical context, there has been a high demand for effective methods that can be used at the early design stage of kinetic façade system [1], [3].

Interworking between physical and digital models provides an efficient hybrid medium for a performance-oriented design of a kinetic façade. The performance-oriented design is an approach to architecture by which building performance is a guiding design principle [5]. It is combined with generative parametric modeling to conduct a form-finding process, in which a computer finds optimal designs while generating and evaluating numerous design alternatives automatically. Using open-source electronic platforms such as Arduino or Raspberry Pi, designers and students build and test the interworked prototypes easily and quickly, even without engineering backgrounds. The physical model with sensors, actuators, and processors interacts with the digital model in a real-time manner.

Until the interworked models emerge as design media, the designer develops design alternatives via multiple iterations of physical and digital models. The phenomena of transition and re-interpretation required to move between media are of great importance as they enhance the design process in cognitive, qualitative, and productive terms [6].

Analog representations are productive than digital media for the initial and fast development of ideas, the stimulation of the imagination, free inquiry, intentional and random cross reference of diverse sources [6]. In the other words, the designer understands geometry, kinetics, and even materiality of the design alternatives while making and operating physical models. However, it is challenging and time-consuming for the designer to make digital models of a kinetic façade due to its complex geometry with motion. It slows down the speed of the iteration, so only the design alternatives converted into the digital models are simulated in the digital environment. Thus, to stimulate the iteration at the initial stage of kinetic façade design, there is a need for the methodology for converting an intuitive physical model into a digital model directly.

Some studies have been done digitizing the shape of a physical model using a 3D scanner like a Microsoft Kinect sensor during the design process [7]. The previous version of this paper proposed the methodology for utilizing the converted digital models in the form-finding process [8]. In those studies, Delaunay triangulation played a pivotal role in converting a point cloud into a triangle mesh. However, it causes two problems. First, the designer should generate separate point clouds for each motion of a kinetic façade. It is a repetitive task and even does not result in a single model which represents continuous motion. Second, the triangle mesh is not directly matched with the geometry of the physical model as well as the one of the designer's cognition.

Because the designer usually deals with rough physical models at the early design stage, topological correspondences between digital and physical models are more efficient for the designer to understand the design alternatives than geometrical

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accuracy. Furthermore, regarding Building Information Modeling (BIM), the triangle mesh is too complicated to adopt architectural components such as steel frames and panels. This paper aims to propose a methodology for generating a single digital model with a motion parameter and a certain topology, from a point cloud of a physical model.

The methodology included a modeling environment and an algorithm processing a point cloud and applied to kinetic façade designs from a design studio.

II. RELATED WORK

A. Design Media for Designing a Kinetic Façade

The designer devises a form for an object without having the actual object in front of him/her [9]. So, the designer needs a medium that interlinks different disciplines in gradually approaching, from the abstract to the concrete, the desired outcome [10]. Media and design process methods associated with media have a direct and essential impact in the way that architecture is conceived, developed and communicated [11].

In designing a kinetic façade, the physical and the digital models are complementary to each other. Physical prototyping enables the designer to have direct engagements with the material properties and behaviors, which are hardly visible in the early design stage [12]. Computer simulations speed up the design process with the comparison of a broader range of design variants, leading to more optimal designs [13].

Fig. 1 Multiple media iteration of analog-digital media interactions [3]

Interworking between physical and digital models provides the designer with another hybrid medium for understanding the connection between the digital design process and its physical actualization. Physical computing including a sensor, processor, and actuators enables physical-digital model dialogue by which the designer can gain feedback from both in real time [14]. The process of evaluating the performance of a kinetic façade design via digital simulations and physical tests enables the designer to gain synergistic potentials of the physical and digital environments. However, this paper focuses on media iterations between physical and digital media before interworking them. Media iterations help designers grasp the differences between media and lead to maximal exploitation of their capabilities [3]. Fig. 1 shows that they are highest at the beginning of the design process and tend to slow down and eventually come to a stop at the end-phases of design development [3]. To accelerate them, the designer needs hybrid media conditions that lower the overhead and labor-intensive use of computer generated visualizations or the effort of transforming and manipulating analog representations [3]. There are two approaches; 'from digital to physical' and 'from physical to digital.' The former is supported by the emerging technologies of digital fabrication such as a 3D printer, a laser cutter, or a robot arm. It makes even delicate and rigid parts of physical scale models based on the geometric information from digital models. The latter needs another approach: reverse engineering.

B. Reverse Engineering and Tangible User Interface

Reverse engineering is the processes of extracting knowledge or design information from anything man-made and reproducing it or reproducing anything based on the extracted information [15]. It is a viable method to create a 3D virtual model of an existing physical part for use in 3D CAD, CAM, CAE (Computer-aided design/ manufacturing/ engineering) or other software [16]. The physical object can be measured using 3D scanning technologies like CMMs (coordinate measuring machines), laser scanners, structured light digitizers, or industrial CT (Computed Tomography) scanning. The measured data alone, usually represented as a point cloud, lack topological information and are often processed and modeled into a more usable format such as a triangular-faced mesh, a set of non-uniform rational basis spline (NURBS) surfaces. The technology generating the 3D model from a point cloud uses volumetric, skeletal models, or even a combination of the two.

In the Architecture, Engineering, and Construction (AEC) fields, 3D scanning techniques such as 3D laser scanning or photogrammetry have been researched extensively as being united with other technologies such as BIM, global positioning systems (GPS), and drones. 3D laser-scanning technology, for example, provides 3D as-built models to an accuracy of 1 mm [17]. This technology, however, is inappropriate for applying to physical scale models from the design process, owing to its significant expense and inability to capture moving objects' X, Y, and Z coordinates. Reverse engineering needs to be reinterpreted from a viewpoint of Human-Computer Interaction (HCI) to be introduced into the design.

The tangible user interface (TUI) is a user interface in which a person interacts with digital information through the physical environment. It takes advantage of human abilities to grasp and manipulate physical objects and materials [18]. A computer mouse, which is mainly used in most of the 3D modeling programs, can be classified as a TUI, but it needs the different actions from the actions of making and controlling the physical model. The MIT Tangible Media Group has explored various TUIs and invented many tabletop applications. Two of them related the architectural design are as follows (Fig. 2).

1) Urp

Urp is urban planning workbench which helps the designer to conduct a series of simulation with the physical scale model. For example, the simple models cast shadows, throw reflections off glass façade surfaces, and visualize pedestrian-level wind patterns on it [19].

2) Illuminating Clay

Illuminating Clay is the topography of a clay landscape model. While the user alters it, changing geometry is captured in real-time by a ceiling-mounted laser scanner. Based on the depth data, landscape analysis functions are operated and projected back into its surface [20].
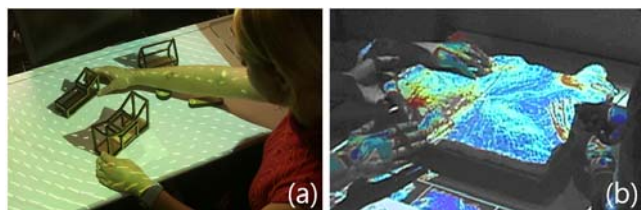
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Fig. 2 (a) Urp [19] and (b) Illuminating Clay [20]

C. Kinect in Designing a Kinetic Façade

Some studies have been done introducing a Microsoft Kinect sensor, developed for Xbox 360 video game console, into the architectural design. A Kinect sensor, equipped with a depth sensor and an RGB camera, provides the designer with a cheaper, faster, and easier 3D scanner. It can be connected with 3D CAD program like Rhino3D which is familiar with the designer. Both students and practicing architects can utilize a Kinect sensor for some of the experimental and 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 [7].

In designing a kinetic façade, a Kinect sensor has used for two purposes. First, a Kinect sensor is used as a motion sensor gathering information to response. Its skeletal tracking is the capability to track the skeleton image of one or two people moving within its field of view for gesture-driven applications. It can be used for tracking hand movement mimicking the Sun's orbit for creating more intuitive design process [21] (Fig. 3).
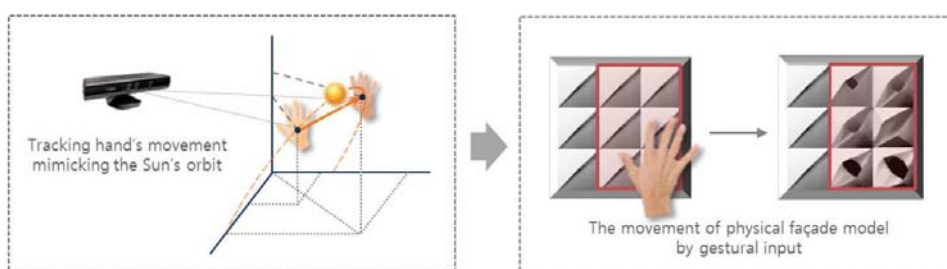

Fig. 3 A Kinect sensor as a motion sensor for gathering information to response [21]

Second, a Kinect sensor is used as a 3D scanner digitizing the shape of a physical model. In the interworked models, the physical model is transformed by physical conditions, not considered on the digital model, including material properties and physical behaviors. In the previous version of this paper mentioned in the introduction, the motions of a kinetic façade were optimized based on the shapes of the physical model (Fig. 4) [8]. As an extended study, this paper focuses on converting the physical model, controlled by hands emerging before the interworked models, into a parametric model including a motion parameter.

Fig. 4 A Kinect sensor as a 3D scanner digitizing the shape of a physical model [8]

III. METHODOLOGY

In designing a kinetic façade, the process, from making a physical model to conducting the performance-oriented design, is divided into following steps:

Step 1. The designer makes a physical model of a kinetic façade.

Step 2. A series of motions of the physical model are digitized using 3D scanning.

Step 3. Several sets of point clouds generated in Step 2 are combined into a single digital model matched with the physical model.

Step 4. Physical properties such as materials are added to the digital model.

Step 5. The performance-oriented design is conducted based on BIM.

This chapter defines the methodology including a modeling environment and an algorithm for converting a point cloud into a digital model.

A. The Proposed Modeling Environment

As shown in Fig. 5, the modeling environment consists of a physical model, a digital model, and 3D scanning. The conditions of each of them are as follows.

1) A Physical Model

In this paper, a physical model of a kinetic façade is paper folding. The folding techniques transform two-dimensional sheets of material into three-dimensional objects [22]. It provides a mechanism of geometry and motion with a kinetic façade because it maintains its length of edges and flatness of faces while being folded. Al Bahar Towers in Dubai is one of the paper folding-inspired projects.

The geometry consists of its definite vertices, edges, and surfaces but it is made of a sheet of white paper. They provide insufficient data with a Kinect sensor and the algorithm. So, to utilize RGB data of a point cloud, the color markers are attached on the feature spots of a physical model. There are two

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different color markers: yellow markers on vertices and blue markers on the center of edges.

2) A Digital Model

A digital model, as expected, satisfies the correspondence with a physical model regarding both geometry and motion.

First, the geometries such as vertices, edges, and faces should correspond with the counterparts of the physical model made by the designer. Based on the geometries, a digital model can be equipped with specific components in BIM.

Second, a digital model should represent its continuous motion of a physical model. Separated point clouds of a physical model need to be combined into a digital model containing parameters related motion for its stability and reusability. However, a point cloud consists of too many vertices to be processed and does not keep list order as the physical model is moved or folded. A digital model needs topological consistency and simple parameters for motion, which enables the form-finding process.

3) 3D Scanning

A Kinect sensor generates a point cloud of a physical model in the coordinate system of Rhino3D using Grasshopper add-in Quokka [7]. The designer makes a series of motion of a kinetic façade by his/her hands in front of a Kinect sensor. A monitor shows a digital model emerged in a real-time to the designer.

The action of folding papers, which is far more intuitive to the designer, replaces for the way of digital modeling using a computer mouse and a keyboard.
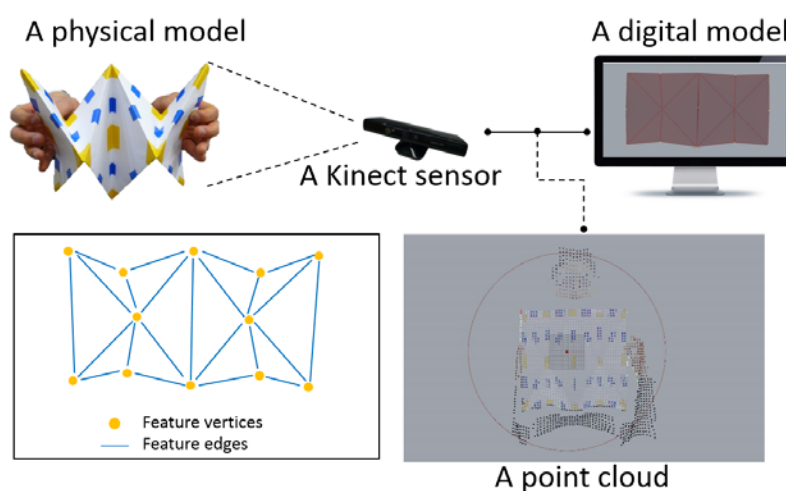

Fig. 5 The proposed modeling environment and feature geometries

B. The Proposed Algorithm

In the proposed algorithm, the target geometry of paper folding consists of feature vertices, edges, and faces as shown in Fig. 5. Only feature vertices of the geometry are extracted from a point cloud of the physical model. Then, feature edges and faces are generated based on them, completing a digital model as shown in Fig. 7.

As shown in Fig. 6, the 3D modeling platform is Rhino3D and Grasshopper, a plug-in for a visual programming language. A series of algorithms from geometry to vision are combined in the proposed algorithm using Grasshopper.

There are two reasons for not utilizing whole vertices of a point cloud. First, at the early design stage, it is more important to generate a digital model matched with a physical model topologically than geometrically. For example, Delaunay triangulation, usually used in converting a point cloud to a 3D surface, builds a complex mesh not a certain geometry with feature vertices, edges of the physical model. Although the mesh is closer to the shape of the physical model geometrically, it is tough to be divided into sub-components.

Second, a point cloud generated on the designer's hands grasping the physical model is unnecessary for generating a target geometry. Because this paper focuses on when the designer actuates the physical model using their hands before electronic actuators such as servomotors or DC motors, the additional vertices should be avoided.

1) Generating Feature Vertices

Only feature vertices should be filtered from thousands of vertices of a cloud point.

a) Filtering by XYZ Coordinates

A 3D scanner generates a point cloud not only on a folding paper but also the designer's body and other obstacles. Only vertices on the surface of the physical model can be filtered by a particular solid such as a box or a sphere surrounding them.

b) Filtering by Yellow Markers

Every vertex of a point cloud has its RGB data taken by an RGB camera of a Kinect sensor and can be filtered by a particular color. A Space defined by relative ratios of Red, Green, and Blue is mapped into a space defined by three primaries, expressed in XYZ coordinates [23]. The difference between two colors is calculated by way of determining the Euclidean distance between two points in the coordinate system [24]. Equation (1) calculates color different (D) between color 1 (R_1, G_1, B_1) and color 2 (R_2, G_2, B_3). Thus, vertices generated

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on the color markers in a certain domain of tolerance are selected.

$$D = \sqrt{(R_2 - R_1)^2 + (G_2 - G_1)^2 + (B_2 - B_1)^2} \quad (1)$$

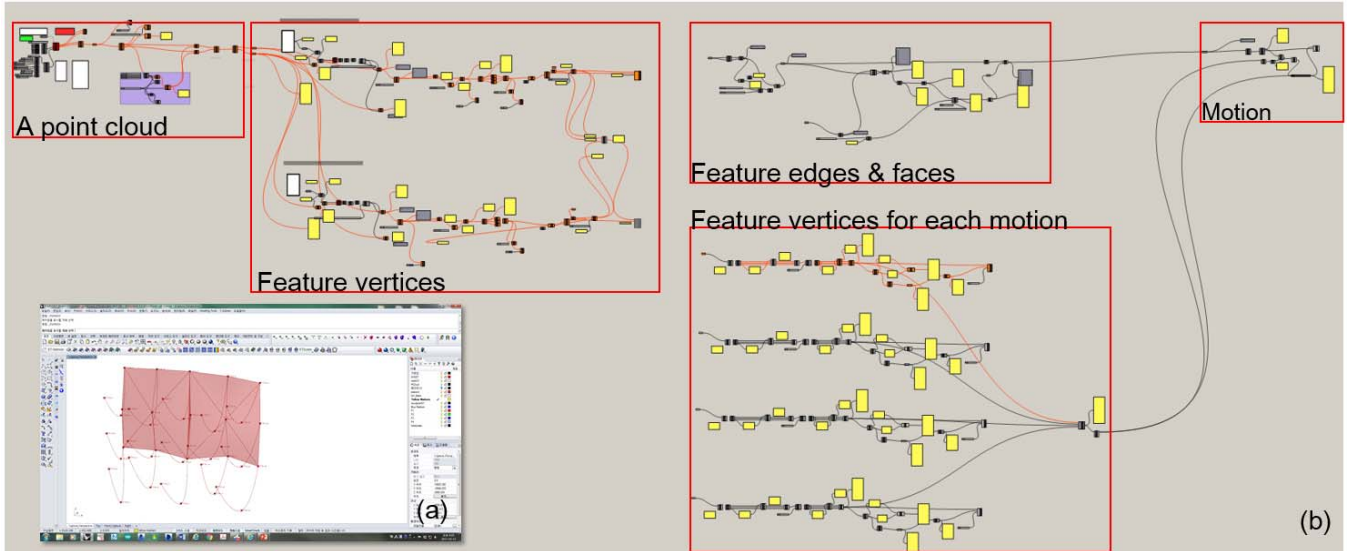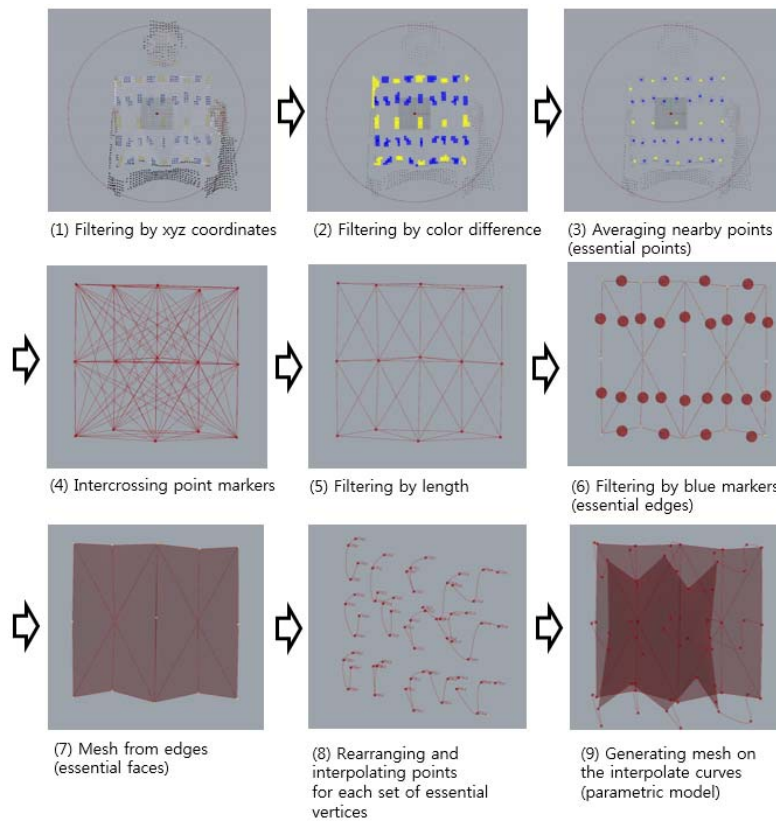Fig. 6 (a) Rhino3D and (b) Grasshopper

(1) Filtering by xyz coordinates

(2) Filtering by color difference

(3) Averaging nearby points (essential points)

(4) Intercrossing point markers

(5) Filtering by length

(6) Filtering by blue markers (essential edges)

(7) Mesh from edges (essential faces)

(8) Rearranging and interpolating points for each set of essential vertices

(9) Generating mesh on the interpolate curves (parametric model)

Fig. 7 The process of generating a digital model from a point cloud

c) Averaging Nearby Points

The vertices on the color markers are grouped by the Euclidean distance. Each average vertex of the groups is matched with each color marker or feature vertex.

2) Generating Feature Edges and Completing a Mesh

Only feature edges connecting feature vertices should be filtered for completing a mesh.

a) Intercrossing Feature Vertices

All possible edges are generated by intercrossing feature

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vertices.

b) Filtering by Length

All possible edges are filtered by a domain of length. If a feature edge is too long compared to others, it should be divided by an additional yellow marker.

c) Filtering by Blue Markers

The remained edges are filtered by the spheres centered on the blue markers on the center of feature edges. Only feature edges connecting feature vertices are intersected with the spheres.

d) Mesh from Edges

A mesh is generated from feature edges. It is matched the physical model.

3) Generating Motion

Separate point clouds for representative motions of a physical model are 3D scanned. Once blue markers are used for generating feature edges, the relationship is reused in the other sets of vertices. However, every set of feature vertices has different list order.

a) Rearranging List Orders of Feature Vertices and Interpolating Them

The list order is rearranged based on the relative position of x and z coordinate. Rail curves, along which the digital model moves, are generated by interpolating vertices on the relatively same position of each set of feature vertices.

b) Generating a Mesh on the Rail Curves

The position of a vertex on the interpolate curve operates as a motion parameter.

IV. Findings

In this chapter, the methodology defined in the previous chapter applies to the physical models inspired paper folding in the design studio. Each resulted digital model verifies whether they correspond with each physical model in term of geometry and motion.

A. Experiment Settings

A series of experiments were conducted in the indoor design studio. The distance between a Kinect sensor and a physical model was 90 cm as shown in Fig. 8 because its default mode generates raw depth data in the region from 80 cm to 400 cm [25]. The sizes of the markers were decided considering the color perception of the algorithm which is more insensitive to yellow than blue. Yellow markers on feature vertices are 20 mm by 20 mm rectangles, and Blue markers on feature edges are 10 mm by 10 mm rectangles.

A Kinect sensor was set up to project the rectangular array of vertices of a point cloud sized 9.5 mm by 9.5 mm onto a flat paper. It was decided considering PC's performance and the size of color markers. The high density of a point cloud interrupts the real-time interaction between physical and digital models.

Four motions for each physical model were captured and

combined into a single parametric model via the algorithm. Three designs were intended to make openings on the façades. Design 1 and 3 were folded by sliding horizontally, while Design 2 is folded by twisting on its axis.
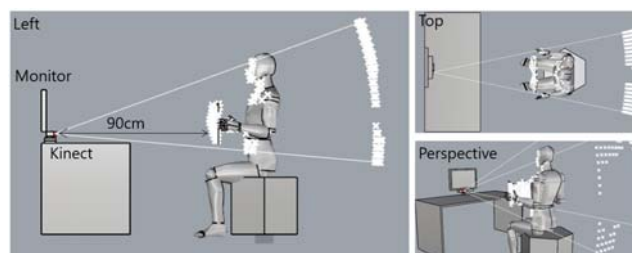

Fig. 8 Experiment settings

B. Experiment Results

Fig. 9 shows a series of experiments and the resulted digital models. All of the digital models corresponded with the physical models topologically with an equal number of feature vertices and edges.

However, the resulted digital models could not reflect the all folding range of the physical model. It means that the folding range of the digital models was reduced. After the physical model was folded at a certain point, the digital model could not be generated anymore. Every physical model has a different folding range according to its geometry and kinetic mechanism.

C. Analyzing Experiment Results

The experiment results are analyzed regarding following four reasons.

1) Discoloration of Color Markers

The indoor lighting environment affects RGB data of color markers. Although the lighting is uniform and not dimmed, the shadow by the physical model itself is inevitable (Design 1 and 3).

2) Normal Direction of Faces

The normal direction of faces of the physical model affects the number of vertices on each color marker. The color markers on the excessively tilted faces are hardly detected because the projected area of color markers decreased (Design 1 and 3).

3) Hidden Parts

A single Kinect sensor cannot generate a point cloud on the parts which are hidden by the other parts of the physical model itself (Design 2).

4) Disposition of Color Markers

If the relative position of color markers changes, the relationship between feature vertices and edges is not maintained anymore (Design 3). Additionally, if two or more same color markers get so close, the algorithm percepts them as a single marker (Design 1 and 3). Thus, the methodology generates the digital model matched with the physical model as far as all of the color markers are captured successfully. To expand the incomplete folding range of the digital model, the designer needs to manipulate or to generate proper feature

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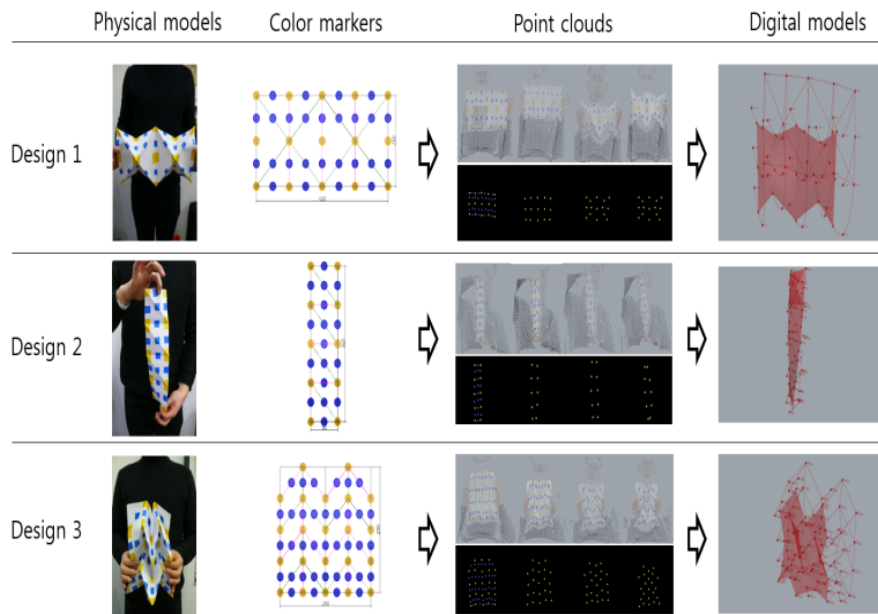Vol:11, No:4, 2017

vertices.

Fig. 9 Experiment results

V. Conclusions

This paper proposed a methodology for converting a physical model into a digital model using a Kinect sensor and color markers in designing a kinetic façade. The methodology was confined to paper folding-inspired kinetic façade designs. It resulted in a digital model which had a certain geometry and a motion parameter. It was intended to help designers not only to save the time to makr a complex digital model but also to stimulate media iterations in the early design stage.

A series of experiments showed the application of the methodology on three design inspired paper folding. The resulted digital model could not represent the whole folding range of the physical model. Multiple Kinect sensors and advanced vision algorithm are expected to improve the performance of the algorithm. Nonetheless, the methodology supported to designers to conduct a performance-oriented design process based on the simulation with rough physical models at the early design stage. Fig. 10 shows an illuminance simulation using Design 2 of chapter 4. The designer can conduct the form-finding process of a kinetic façade with digital models including a motion parameter. More complex simulations are available when the digital model is equipped with more specific architectural components in BIM.

This paper has some limitations and requires future works. First, just three paper folding-inspired designs are verified. Various examples of a kinetic façade are supposed to need a different approach from the methodology for paper folding. For example, the digital model of flexible materials needs to include an elasticity parameter as well as a motion parameter. Second, the actual effects on multiple iterations of physical and digital models are not verified from the viewpoint of the designer. The overall changes to the design process occurred by the methodology need to be researched.
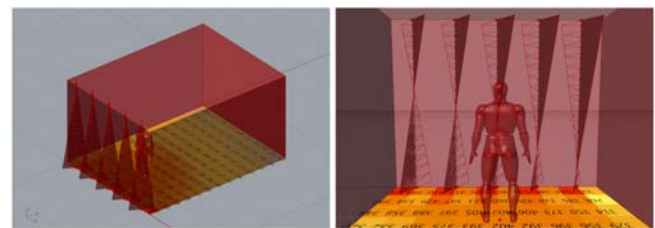

Fig. 10 The performance-oriented design process based on the simulation with digital models from rough physical models at the early design stage

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