Interactive Kinetic Media Facades: A Pedagogical Design System to Support an Integrated Virtual-Physical Prototyping Environment in the Design Process of Media Facades

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Abstract
Today, media facades play a significant role in our urban environments as media technologies continue to advance, aided by general systems theory and cybernetics. These media facades have taken new directions, toward holistic forms of kinetic, media, and interactive architecture, well beyond responsive architecture. Considering the move toward increased integration, a new pedagogical design tool for helping architectural designers and students understand kinesis and interaction more fully is now needed. For this, a design system that supports an associated, integrated virtual-physical prototyping environment based on multi-agent-models and Delta robot kinematics is proposed, implemented, and tested here. This research begins by exploring the latest cases of media facades, focusing on physical motions and the flow of information. Through analysis and classification, this research presents a theoretical model which consists of a tectonic model and an interactive model. Moreover, to prove the viability of these proposed models, an integrated virtual-physical prototyping environment is offered. The ultimate objective of this study is to assist, enhance, and expand the scope of media facades by proposing new ways of constructing, controlling, and simulating media facades by means of a new pedagogical design tool. Thus, this research contributes to pedagogy by allowing students and designers to fully explore and better understand interaction and kinesis in media facade design.

Keywords: prototyping; interactive kinetic media facades; pedagogical design system; Delta robot

1. Introduction
Today, media facades play a significant part in our urban environments with the advance of media technologies, greatly aided by general systems theory and cybernetics. Now, new architectural facades that utilize robotics and interactive technology are emerging through new media. These new media support interaction and kinesis beyond simply the form of conventional media screens. These technologies have enabled some of the visionary ideas of early cybernetics, not only in terms of their physical realization, but also by taking media facade design in important new directions.

The new directions have been taken toward holistic forms of kinetic, media, and interactive architecture beyond responsive architecture. With regard to this kind of synthesis between different emerging technologies, it becomes necessary to expand our understanding of architectural concepts such as those of the "morphological," "spatial," and "temporal" (James and Nagasaka, 2011). In order to help architectural students fully understand these expanded architectural concepts, technology-based classes such as physical computing and computer programming have been offered in architectural education. Despite these efforts, however, it has not been easy for architectural designers and students to understand and learn about emerging technologies both practically and theoretically—it has been equally as difficult to apply these technologies to their designs no matter how passionate they might be for these new technologies. Thus, we need a new pedagogical design tool for interactive kinetic media facades that is both physical and digital so that it may help architectural designers and students better comprehend the principles of kinesis and interaction. This can be achieved by means of the design tool, as it can be used to quickly construct and manipulate different motions within their design process.

Kinetic media facades are created by joining together kinetic design and its representation. Interactive kinetic media facades display data generated by diverse computational algorithms and by simple image-based representations such as images, texts, and videos. In addition, the kinetic representations in these media facades can be created through new ways of addressing, controlling, and simulating the
relationship between the digital properties of the input and the physical properties of the output. These new ways of controlling kinesis and interaction requires an equally new design system that supports an associated, integrated virtual-physical prototyping environment.

The goal of this research is to propose and develop a pedagogical design system for interactive kinetic media facades, which will help architectural designers and students generate creative ideas and concepts and improve communication in motion prototyping from the early design stages to the final design stage. This research is the second part of our long-term project to develop a hybrid prototyping environment for interactive kinetic media facade designs that incorporate both software and hardware. As the first part of this long-term research, the design parameters (Fig.1.) and the tectonic model for effectively constructing media facades were established as a design method through the exploration and classification of different state-of-the-art media facades (Park et al., 2011). Based on the design methodology, a prototype of a multi-agent-based media facade system was provided as software. This current study proposes a physical prototyping environment as a counterpart to the software, one that supports a variety of electronic and mechanical motions based on multi-agent-models and Delta robot kinematics. It will also propose an effective method for controlling kinesis and interaction by integrating the software and the hardware.

Proposing this new hybrid design system confronts a new range of research problems. How quickly can designers and students in the design process construct different motions that are employed in the existing kinetic media facade? And how can they display different representations by means of controlling motions in their kinetic design? More specifically, how can we integrate different motions into one module of a kinetic media facade? How can we create different motions beyond those of the existing kinetic media facade? And how can we control the various modules for displaying different representations on a kinetic media facade?

This research starts by exploring the latest cases of kinetic media facades, focusing on physical motions and the flow of information. By analyzing and classifying them, this study constructs both a theoretical model which consists of a tectonic model (that effectively provides motion construction) as well as an interactive model (that provides different representations through motion control). Furthermore, to prove the viability of these proposed models, an integrated virtual-physical prototyping environment is developed, implemented, and tested here.

This study is meant to assist, enhance, and expand the scope of media facades by proposing new methods of constructing, controlling, and simulating media facades through the use of a new pedagogical design tool. Therefore, this study contributes to pedagogy by allowing students and designers to fully explore and better understand interaction and kinesis in the design process of a media facade and also to generate better design products.

2. Interactive Kinetic Media Facades: New Directions

Since Gordon Pask's (1969) investigation of the connection between architecture and cybernetics, attempts to apply the vision of early cybernetics to architecture as "responsive architecture" were made by architects such as Nicholas Negroponte (1975) and Cedric Price. Moreover, in the 1970s, Zuk and Clark (1970) attempted to introduce physicality to earlier theoretical propositions with their proposals for a new, kinetic architecture in the form of adaptable architecture.

Today, technological and conceptual advances in fields such as artificial intelligence, robotics, and materials science have allowed the early visionary concepts to be realized in new ways. Current media facades that possess communicative properties, which employ diverse representations, integrate aspects of kinetic, responsive, intelligent, and interactive architecture in terms of: (1) the kinetic properties of architecture which incorporate structural movements, (2) the reactive properties with which responsive architecture responds to environments, (3) the adaptive properties of control systems that intelligent facades possess, and (4) the properties of surface-based interaction between people and buildings.

In interactive architecture, the surface-based interaction advances toward true interaction. This occurs through a multi-loop system by a series of experimental explorations that correspond to evolving individual, societal, and environmental needs based on creative ideas and emerging technologies. This progress emerges from the application of intelligent features.
such as "complexity," "autopoeisis," "network," "feedback loops as learning," and "plug-and-play" to basic structures involving the input-control-output (Senagala, 2006). In order to facilitate the application of these intelligent features, interactive architecture requires: automated kinetic systems with "embedded," "computational" control devices; "decentralized," "emergent," "bottom-up" control; "modular," "robotic" control systems; "biometric" recognition processes; and ultimately, "bio-robotic" control systems that adapt all sorts of actuators and sensors at the level of materials (Bier and Knight, 2010).

The design outcome of media facade systems integrated with intelligent features is to visualize and represent the motion patterns built by the forms, shapes, or colors that are generated through the interaction between the built components themselves or between environments and built components. This outcome is achieved through a holistic understanding of technology, design, and content.

Our challenge for interactive kinetic media facades concerns the visualization of intelligent features with physical movements via interaction, including a variety of representations with media facades. This challenge can be realized through a new understanding of interaction and motion control via media facades. To effectively achieve this, a new physical prototyping environment is needed.

3. A New Prototyping Environment

In kinetic design, kinesis is programmed for control and is transformed with interaction. Frens (2006) discusses the need for the unity of form, interaction, and function in interactive product design. He argues that these three aspects are related to each other and cannot be designed separately. The interconnectedness of kinetic form, function, and interaction should determine the development of any computational object. This interaction must contribute in more detailed ways from the early stages to the final stage in the design process—much more than in the traditional design process, which considers form and function together (Parkes, 2009).

In order to effectively consider kinetic form, interaction, and function together in the design process, physical prototyping becomes increasingly important. Through motion prototyping, such as "bodily engagement" and "tactile manipulation," designers can gain a deeper understanding and a more intuitive experience (Parkes and Ishii, 2009). Moreover, designers can identify, enhance, or modify their ideas through different kinds of feedback both from and between users with regard to final design products.

With the recent movement in architecture—that of incorporating kinesis and interaction—electronic prototyping (e.g. physical computing) is being integrated into architectural education. However, it is difficult for architectural designers or students to produce their design alternatives from working prototypes due to the mismatch between their capabilities in design and technology (or physical computing). The discipline still lacks sufficient media that can actively enrich and expand their design process. Thus, a new prototyping environment as design tool is needed.

In interactive kinetic media facade design, an integrated virtual-physical prototyping environment that supports modeling, quick fabrication methods, motion prototyping, and real-time simulation, will enable designers to generate creative ideas and concepts in the early design stages, as well as confront and anticipate many of the issues that will emerge when building at full scale in the final design stage.

4. Analysis of Cases

In order to construct a theoretical model for interactive kinetic media facades, we have explored different cases of the latest media facades, focusing on what kinds of kinesis these cases used and how information flowed within the systems. Table 1. shows the process of analyzing the cases.

Table 1. The Analytic Diagram of Cases
The cases were investigated through the lens of the three factors for an interactive system: content, interaction, and display. Through this exploration, a taxonomy of interactive kinetic media facades was constructed (Fig.2.). This taxonomy allows us to understand the relationships between each element of the three factors in terms of information flow, since the key element that is looping through an interactive system is information (Crawford, 2002).

The content as input is characterized by image-driven data and/or embodiment-driven data depending on the type of sensors. Also, the interaction as control can normally be classified if embodiment-driven data or image-driven data is directly employed in a control application or is indirectly employed via the graphic application of a central computer.

The display as output is categorized by an electronic display and mechanical display. A mechanical display consists of an actuator that constitutes mechanical movement, a surface that constitutes an architectural shape, and mechanical parts that change the direction of force. The relationship between the mechanical movement and the architectural shape minimizes the change of the direction of force by using one or several mechanical parts.

By analyzing these cases, media facades can be characterized depending on the level of interaction. A person acts as a learning system when he and a computer are coupled together, since people have the natural ability to "comprehend," "reason," and "learn." An interactive system that includes people can thus be considered as a natural single-loop system with intended data. This basic system can be expanded by adding a single-loop or multi-loop system to it. On the other hand, a responsive system normally employs the embodiment-driven data of unintended data, although it can utilize its image-driven data. Most responsive systems are operated as a linear system in which input data and output data are not coupled with each other. The basic form of a responsive system can be expanded by adding a linear or single-loop system to it.

Displays in media facades appear in the form of a modular system that acts as the equivalent of pixels. To maximize motion and/or light, the geometry and materials of the facade’s surface plays an important part. In the present facades, the mechanical parts behind the surface appear as several different types of limited movements.

In order to provide a new prototyping environment in this study, the challenge is as follows: (1) integrating an interactive system with an expressive and responsive system, (2) generating data visualizations through the interaction between entities, and (3) expanding the existing movement of kinetic media facades.

5. Theoretical Model

The theoretical model is based on an analysis of different interactive media facades. The goal of the theoretical model is to represent media facades with a set of variables and their interrelationships before developing our prototyping environment.

5.1 Tectonic Model to Design Motions

A tectonic model of interactive media facades with which designers can effectively generate an interactive kinetic media facade was proposed in a pilot study of this research by Park et al. (2011). The tectonic model provides a framework for building the media facades with a basic layered structure through their design parameters and their interrelationships (Fig.3.).

The interactive kinetic media facades in this tectonic model can be built by a combination of three controllable elements: "materiality," "visualization," and "physicality." The motion properties for "visualization," such as speed acceleration, direction, delay, and twitter, are closely related to the interactive model above. "Materiality" and "physicality" can be regarded as elements in the building of the physical model. "Materiality" is related to the surface design in terms of generating shapes, designing patterns, and choosing materials. Moreover, designers can decide on constructing either an electronic facade or a mechanical facade for their design in the "components." The motions of the mechanical components can be characterized by several axes of motion: radial, vertical, and horizontal. If controllable components, which provide the basic movement to designers, are offered, they can then build interactive media building
facades quickly and creatively by designing only a surface. By separating the internal and external elements of interactive media facades, designers can design interactive media facades more effectively.

5.2. Interactive Model as a Theoretical Model

The purpose of the interactive model on a theoretical level is to provide an integrated approach capable of providing all types of representation and to support representations which engage "intelligent" objects in a multi-loop system.

5.2.1 Constructing an Interactive Model

Through an analysis of the information flow, media facades are categorized into three types as shown in Fig.4.; (a), (b), and (c) are normally shown in both responsive and interactive systems since the software of a central computer controls the hardware, while (c) is only for interactive systems. Case (c) shows the way that information via the individual input device controls hardware separately—one input device controls one piece of hardware. The individual control of the hardware can enable a wide range of possibilities for enhancing "playful" interaction between multiple persons in order to grab the user's attention.

Based on an analysis of the information flow, the integrated structure of interaction can be proposed as shown in (d). To achieve the integrated capability, the software controls the hardware individually or collectively with multiple or single units of data that come from either single or multiple input devices. An interactive system can be built as a single-loop system by simply adding a linear system in the relationship between software and hardware. By switching the counterparts of interaction or removing input devices, this model can serve as a responsive or expressive system.

However, this model does not support a multi-loop system. In order to support a multi-loop system, this model needs to be revised as shown in (e). This interactive model is completed by building a feedback loop structure between the software and each physical component of hardware. For the feedback loop, the software compares and changes the goal to the interaction between the physical components themselves. This model features bi-directional communication between software and hardware and interaction between two or more active parties.

6. Integrated Physical-Virtual Prototyping Environment

6.1 System Overview

The prototyping environment developed by the author consists of two design applications: software and hardware. The software functions both as a simulator as well as a controller that includes the function of input devices and datasets. It allows for designing interactive kinetic media facades, generating multiple kinds of representations through a variety of movements based on a multi-loop system, and controlling the hardware. The hardware, which consists of robotic blocks as an embedded system, allows for constructing the structure of their physical working models quickly. The interactive kinetic media facades can be built by adding a surface onto the structure, and they can be experimented on with different materials. The robotic blocks can take advantage of the combination of the editability of computer data and the physical immediacy of a tangible model, and they can provide a means for the expression and investigation of both patterns and processes not possible with existing materials.

The prototyping environment can physically and digitally support the construction of interactive kinetic media facades by controlling different design parameters and then simulating multiple kinds of representations with different movements. To free the kinesis of the mechanical components, the kinematics of a parallel Delta robot can be applied to the structure of the robotic block, which in turn makes free motions within the block possible by supporting three translational degrees of freedom and one rotational degree of freedom. The software and the hardware are continually interconnected and then made to bi-directionally communicate through transferring data to a group of robotic blocks or individual robotic blocks. Fig.5. illustrates the overview of the prototyping environment.

6.2 Robotic Module Using Delta Robot

This research integrates all possible forms of kinesis, such as vertical, radial, and linear movements, into one robotic block for the structure of interactive kinetic media facades. The robotic block was developed...
by applying the technology of a Delta robot to the motion of the structure. The Delta robot, which was invented by Reymond Clavel in the early 80's, is a type of industrial parallel robot (Clavel, 1988). It is composed of three arms connected to universal joints at the base. The key feature of this robot is to have three translational degrees and one rotational degree of freedom by using parallelograms in the arms (Fig.6).

The Delta robot kinematics, which consist of inverse and forward kinematics, are coded with programming languages by an author with an understanding of mathematics, as based on Zsomber-Murray's paper, "Descriptive Geometric Kinematic Analysis of Clavel's 'Delta' Robot" (2004). The embodiment of the code aims to exploit the full reach of the moving points of the Delta robot within a limited space. This built code was used in both the hardware and software.

6.3 Controlling the Interaction between the Software and the Robotic Blocks

Three ways of effectively controlling the relationship between software and hardware (robotic blocks) are proposed based on the interactive model: group control, individual control, and interaction between the robotic blocks (Fig.7).

Group control and individual control are basic ways of controlling hardware via software. In both controls, the relationship between software and hardware is uni-directional. Group control can take advantage of algorithms for motions in which entities depend on each other. The software and hardware independently operate the same motion algorithms that they respectively own. The hardware can be controlled by transferring key parameters which can control motion patterns from the software.

Individual control entails users in the software controlling each slave's microcontroller of the robotic blocks directly with parameters. This individual control enables users to merely use several robotic blocks. With this individual control, users can transfer the data they want to send to the robotic blocks. Desired individual motions are then controlled through a group control approach. In addition, users can use the robotic blocks as pixels for displaying images; they can display algorithms by which entities work independently of each other, such as in swarm or flocking algorithms.

7. Experimentation

This research investigates how to represent diverse physical motion patterns with the prototyping environment. The goal of this experimentation is to prove the validity of three ways of controlling interaction: group control, individual control, and interaction between robotic blocks. The key criteria for these experiments are: (1) what styles of interaction are most effective for the types of control and (2) how we can fully support physical kinesis with different dynamic motions generated by computational design algorithms.

In this experiment, computational algorithms that designers have recently employed for their digital designs were utilized to represent and control physical motions with diverse parameters for the algorithms that could be combined with actual input data. This is effective for achieving our goal in that we can intuitively and clearly observe the abstract looping information flow through graphical means (Friedman, 2008). In addition, with the advent of algorithmic design, computational design algorithms can now be visually represented on the interactive kinetic media facades as a way of communicating information for both aesthetics and functionality. Experiments for visualizing data through the computational algorithms are therefore warranted and justified.

7.1 Group Control of the Robotic Blocks

Group control was tested with two algorithms: the wave pattern and the vector field. The software and hardware (robotic blocks) each have an application that was created by the same algorithms for wave patterns and vector fields. Both systems are operated independently. The software can control the hardware by transferring the key parameters of these algorithms. Group control can be effective for constructing a responsive display with embodiment-driven data by continuously providing changing key parameters. Fig.8. shows the mechanism of group control and its application.

Since Delta robot kinematics can provide diverse movements in the manner of basic motions such as piston, linear, and radial motions, a variety of motion patterns can be produced by adding a wave function.

7.2 Individual Control of the Robotic Blocks

Individual control allows users to directly control each robotic block. This experiment investigates the possibility of robotic blocks acting as the pixels of a
screen. This kind of individual control can be effective for constructing expressive displays with image-driven data or embodiment-driven data. In this way, an image representation and algorithm of agent behaviors were tested experimentally. Fig.9. shows the algorithms for Agent Behaviors and their applications.

7.3 Interaction between the Robotic Blocks

Another method of visualizing data in the hardware is through direct interaction between the physical robotic blocks themselves. In an architectural context, the interaction between robots is applied to self-reconfiguring modular robots that change their own shape by rearranging the connectivity of their parts in order to adapt to new circumstances or perform new tasks. However, the interaction between the self-reconfiguring modular robots can be regarded as a reaction with a fixed goal, not true interaction.

The prototyping environment, which proposes bi-communication between the software and the hardware, becomes a multi-loop system based on interactions between the robotic blocks. This has the potential for applying intelligent features and generating new representations. In this experiment, two main points were proposed and tested: (1) data transfer between the robotic blocks and (2) the bi-communication between the software and the hardware.

In Fig.10., the logic of interaction between robotic blocks is shown. Here, the user is allowed to simulate physical interaction between robotic blocks without any input from sensors because the robot blocks are connected by i2c technology. The robotic blocks go beyond the capability of existing physical or virtual agent systems since each robotic block can directly communicate with the software in order to support a multi-loop system. On a theoretical level, the proposed hybrid system functions as a rule-based system which is a prerequisite to an artificial intelligence system. On a practical level, this same system is flexible enough to accommodate physical extensions. However, such physical extensions may or may not affect the theoretical scheme. So, for example, the attachment of sensors to the microcontrollers in each robotic block may have a physical effect but not necessarily an effect on the rule structure of the system. The possibility of using external inputs to the system is not implemented in this research but may become the object of another study.

This way of controlling interaction between robotic blocks may have a new potential to visualize data depending on different design scenarios. Such a possibility that involves design with actual input sensors is left for future research.

8. Test Cases

The common goal of interactive kinetic media facades is to integrate media, information technology, and architecture. This requires designers/engineers to design a control system and data input, as well as the physical components (Moloney, 2011). As the motions generated by media and information technology are coupled with the surface, interactive kinetic media facades are completed. The goal of these test cases is to prove the validity of the constructed prototyping environment as a pedagogical design tool for interactive kinetic media facades.

In architecture that features motion, surfaces are connected by mechanical parts to form movable elements (Schumacher, et. al., 2010). These kinetic products are usually created by changing the direction
of force through the combination of one or several mechanical parts. Since the hardware of the hybrid system has the ability to provide almost all the possible motions for feasible interactive kinetic media facades, the surface as movable elements can minimize mechanical parts such as hinges, slides, and gears in order to construct cases with different kinds of kinesis.

Three successful and well-known cases of the interactive kinetic media facade were tested: Hyposurface by Mark Goulthrope & dECOi archtects, Arab World Institute by Jean Nouvel, and Galleria Department Store by UN Studio. The cases are built by exploring the relation between motions and surface design, while generating kinetic parts (Fig.11.).

9. Conclusion and Further Research

The research provided here aims to propose and develop a pedagogical design system for interactive kinetic media facades that supports a newly associated, integrated virtual-physical prototyping environment. In order to achieve this purpose, this study formulates theoretical models— in terms of an interactive model and tectonic approach. By analyzing and categorizing related works.

From this research, key discoveries were made: (1) Interaction is closely related to the control part of systems rather than surface-based interaction by input devices, (2) diverse types of interaction are generated in the exploration of the relationship between the hardware and software, and (3) interaction is related to surface design and content design based on kinesis. From these findings, an integrated approach that considers content, interaction, and display together is required as a method for kinetic media facade design.

Therefore, this study is expected to contribute to helping designers and students assist, enhance, and expand the scope of interactive kinetic media facades through the understanding of interaction and kinesis. It ultimately aims to generate a better design product with our pedagogical design tool for small-scale experimentation, and seeks to move this emerging architectural system in a new direction.

The next stage of this research is to examine the possibility of its commercial use. Further enhancements to the design system to that end would include: (1) developing the software that is able to generate complex geometric forms, (2) developing effective algorithms for the scalability of hardware, and (3) developing hardware that fully supports the universal degrees of freedom.

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