International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:11, No:10, 2017

A Biomimetic Approach for the Multi-Objective Optimization of Kinetic Façade Design

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***Abstract*—**A kinetic façade responds to user requirements and environmental conditions. In designing a kinetic façade, kinetic patterns play a key role in determining its performance. This paper proposes a biomimetic method for the multi-objective optimization for kinetic façade design. The autonomous decentralized control system is combined with flocking algorithm. The flocking agents are autonomously reacting to sensor values and bring about kinetic patterns changing over time. A series of experiments were conducted to verify the potential and limitations of the flocking based decentralized control. As a result, it could show the highest performance balancing multiple objectives such as solar radiation and openness among the comparison group.

***Keywords*—**Biomimicry, flocking algorithm, autonomous decentralized control, multi-objective optimization.

I. INTRODUCTION

THE building envelope is a building component which affects energy consumption, indoor environmental quality, and the image of the building. As a barrier, it controls numerous distinct factors such as heat, moisture, air, and other flows between indoor and outdoor environments. At the same time, all the elements need to satisfy overall requirements such as strength, rigidity, durability, aesthetics and even economic feasibility [1]. Designers and engineers conduct a series of process of optimizing several of these items simultaneously because they have strong interrelationships each other. Nevertheless, in the traditional static system, it offers satisfactory performance only under certain circumstances which are expected during the design process. It means that the performance is not guaranteed if the operating environment or system requirements change over time [2]. To overcome the limitations, architectural designers have introduced robustness, through, e.g., oversizing, portioning, redundancy, and scalability [3]. However, the strategy cannot cope with unexpected conditions of contemporary cities which are overcrowded and complex.

A kinetic façade alters the function and form according to user requirements and environmental conditions [4]. It consists of embedded computation for intelligence and physical counterparts for kinetics [5]. When it comes to designing kinetic façades, the designer should consider kinetic mechanism, material behavior and kinetic pattern, not dealt with in the static system [6]. Recently, computer simulation backs up performance-oriented design, which generates and analyze the performance of a lot of design alternatives from the early design phase. While a form of a static façade is optimized in the design stage, a kinetic facade adapt to through changing its form even in its operation stage. In other words, form-finding of kinetic façade design keeps happening after construction.

A kinetic façade is a combination of multiple kinetic units covering the building envelope. It operates through so-called kinetic patterns, which result from every unit. Additionally, the immediate reaction is essential for delivering its high performance. If every spot on the surface is under the same condition, the control of the units is simple. However, each unit is confronted with different user requirements and environmental conditions according to its location. The reasons making the conditions different are as follows.

(1) Shadow and reflected light from nearby buildings;
(2) Form of the building itself (especially freeform surface);
(3) Space program and user requirements.

It is hard to predict how these conditions will change because they are affected by the form of the kinetic facade itself. Therefore, it is essential for a real-time control system determining the best movements of every unit considering the multiple objectives.

In the same vein, robotic researchers introduced flocking from a biomimetic approach to resolving complex problems like cooperative control for multiple autonomous vehicles [7]. Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature’s time-tested patterns and strategies [8]. In architectural design, it has been adopted to the process of finding an optimal form. Recently, the trend is changing from strict geometrical order to movements and flowing spaces [9].

When it comes to Climate Adaptive Building Shells (CABS) including a kinetic facade, nature is the most inspiring thing [2]. There are three biomimetic approaches.

(1) Principles to respond to the environment such as phototropism and heliotropism
(2) Kinematics of moving parts
(3) Materiality of smart material

Compared with kinematics and materiality, there are fewer studies on the control system of movements making kinetic patterns. This research aims at proposing a biomimetic approach for kinetic façade design using the multi-objective optimization.

CABS can be divided into the macro scale and the micro scale in terms of scales of adaptation [2]. The adjustment of the

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macro scale is mainly achieved by changing the arrangement of the facade through the moving parts. The adaptation of the micro scale results from a change in the internal structure of the smart material. In this study, a kinetic façade is limited to the macro scale which is considered to be the most conservative solution for the adaptive behavior.

This study is related to not only the operation phase but also the early design phase. The reason is that designers need to explore a potential of a certain alternative while balancing kinetic mechanism, material behavior and kinetic pattern for successful kinetic façade design.

As a biomimetic methodology, flocking algorithm is introduced to the control system of a kinetic façade because each agent or unit moves according to simple logic, but the whole pursues homeostasis. The kinetic façade unit is fixed in position, while the flocking algorithm is about moving agents. Therefore, it is important to determine the relationship between the kinetic units and flocking agents.

II. BACKGROUNDS

A. Control Systems of a Kinetic Facade

Extrinsic controls can be classified into three types in terms of the relationships between the micro-controllers and a central control unit: centralized control, distributed control, and autonomous decentralized control [10]. In centralized control, every unit is driven by a supervisory control unit. In decentralized control, in contrary, every unit is controlled via embedded computation in its local processor.

Decentralized control is superior to traditional centralized control in terms of efficiency, redundancy, low cost, calculation time, and functional and compositional freedom. Today, the realization of decentralized control is made possible by the development of parametric design tools and the dissemination of inexpensive and high-performance physical computing devices.

Decentralized control can be developed into autonomous decentralized control. In autonomous decentralized control, each unit receives not only data from the environmental conditions but also data inputs from the adjacent components as well. It needs a self-organizing system such as cellular automata and flocking algorithm [4].

B. Flocking Algorithm

With emerging computing technologies, biomimicry can provide a methodology to solve the complex problems which were not resolved by traditional techniques and approaches. Swarm intelligence is a decentralized and self-organized system mimicking creatures in the computer simulation or mathematical model [11].

This paper refers to flocking algorithm which mimics the behavior exhibited when a group of birds, called a flock, are foraging or in flight. It is considered an emergent behavior arising from simple rules such as separation, alignment, cohesion and avoidance followed by individuals without any central coordination as shown in Fig. 1 [12].

It has been mainly used to create crowds that are realistic in the fields of animation and games. Beyond the screen, it can be used as autonomous control systems of multi-robots or unmanned air vehicles. It also gave rise to particle swarm optimization (PSO), a method for optimization problem [13]. In architecture, it was introduced to generate architectural forms and to analyze various urban and social phenomena.

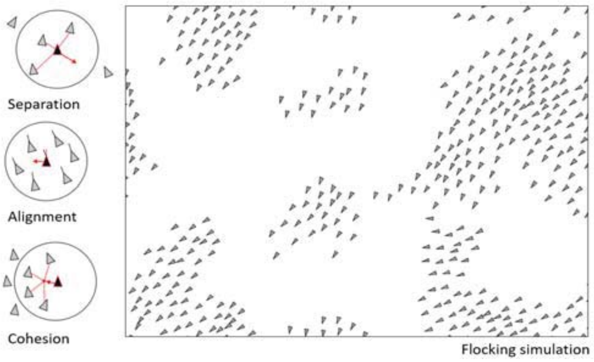


Fig. 1 Basic rules of flocking algorithm

III. METHODOLOGY

In this chapter, a methodology is proposed to generate optimized motion of a kinetic facade by incorporating the flocking algorithm into decentralized control.

Simple decentralized control ignores the effect of each unit on surrounding units since all units operate simultaneously. However, upper units can cast shadows on lower units. In other words, it may not be the best for all units to react directly to the sensor.

By introducing the movement of the flocking agents into the control system of a kinetic facade, every unit reacts with a time interval. In short, they determine the order of the reactions. The following effects can be expected. First, despite a small number of units operating temporarily, performance can maintain constant in the long run. Second, it can quickly cope with the unpredictable local change of bio-climate or space program with the natural kinetic pattern. As a result, multi-objective optimization will be possible, which will enable the overall performance improvement of the entire building.

A. System Structure

As shown in Fig. 2, the system has five layers; grid, external sensors, flocking agents, moving parts, and internal sensors. A façade surface is divided into grids according to the size and shape of its units. Each unit consists of sensors, actuators, moving parts, and a local processor.

The multiple agents are generated on the layer of flocking agents. The agents control the actuators indirectly while autonomously reacting to external sensor values. The local processor commands its actuators. As a result, the moving parts change their shapes to improve the building performance.

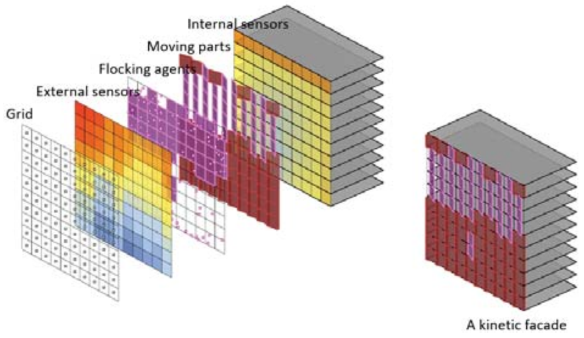


Fig. 2 System structure

B. Processing

The detailed sequence in which the flocking algorithm applies to sensor values is as shown in Fig. 3. It is assumed that an actuation matches with a certain condition of each unit.

1) Stage 1: Sensing Point Filtering

The sensing points represent not only the positions of the sensors but also the units. Pre-set weights or scenarios determine the priority between criteria of each unit. Through two filtering processes, the target points remain from all the sensing points and attract the agents. The primary filtering is the process of determining the units to be controlled by the agents. By adjusting the domain of the sensor values, the reaction zone on the façade surface can be changed. However, the sensing points confine the agents because they are regularly arranged in the reaction zone. Through the secondary filtering, only a part of the first filtered sensing points remains randomly. The second filtered points play a role as target points for the agents to gather around. The random seed of the secondary filtering changes with sufficient time for the agent to disperse. As a result, the agents can operate all the units in the reaction zone on average.

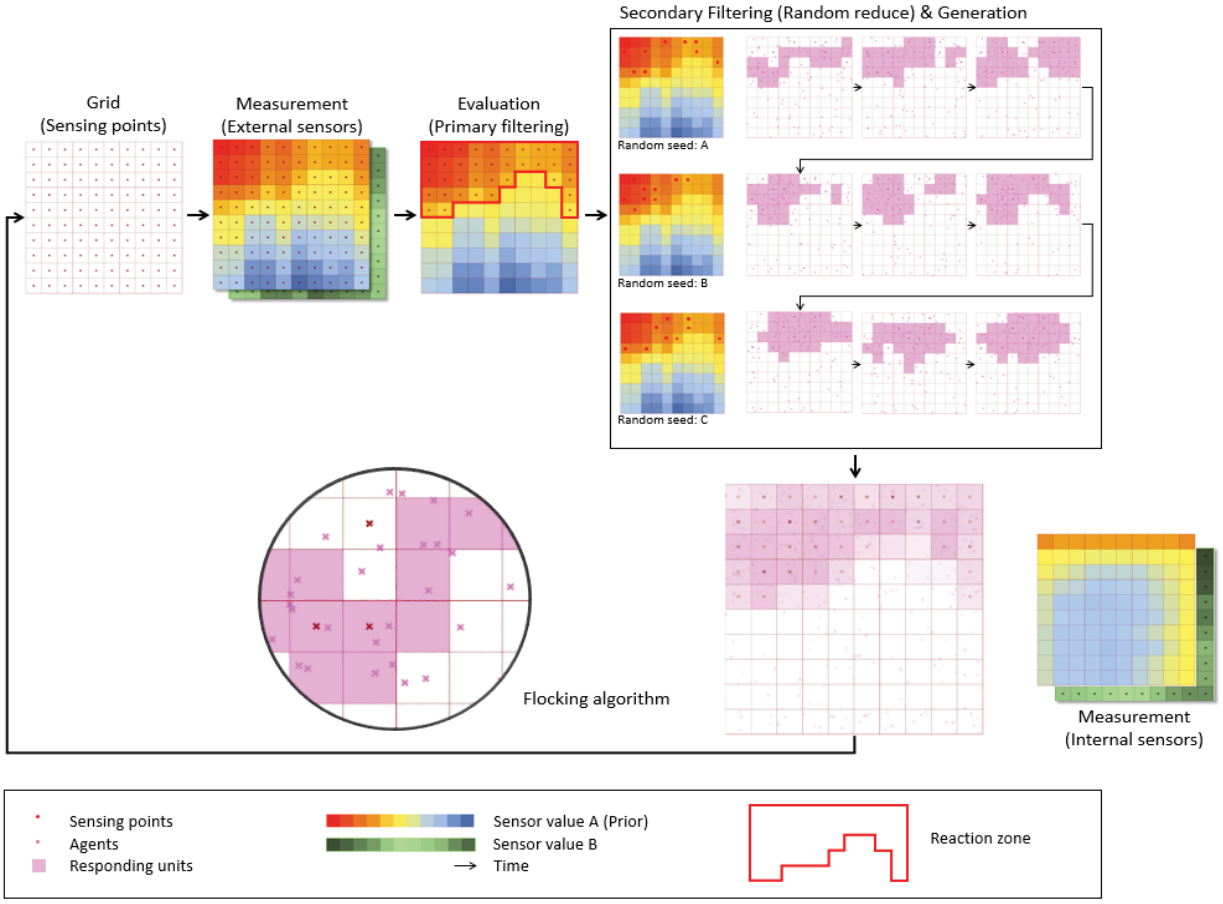


Fig. 3 The sequence of processing

2) Stage 2: Flocking Algorithm

An agent has a limited lifetime and emerges at a random spot on the facade surface at regular intervals. The number of all the flocking agents is proportional to that of first filtered sensing points. The number of agents on each grid operates each unit. Steering forces affecting agents are as follows: separate force, view force, seek force. The agents do not need cohese force and align force because they should remain away from each other not to operate the units out of the reaction zone. As a result, the flocking agents are distributed all over the facade, enabling rapid response to unpredictable local changes. The units which are not affected by the flocking agents operate according to the subordinate scenario. The kinetic facade adapts to changing environments by repeating the process of generation, measurement, and evaluation.

IV. EXPERIMENTS

This chapter confirms that the flocking-based decentralized control (FDC) proposed in the previous chapter solves multi-objective optimization of a kinetic facade. The goal of optimization is to maximize openness while minimizing the amount of radiation on the curtain wall inside the kinetic facade.

A series of experiments were conducted in a digital environment. Rhino 3D is the main tool for 3D modeling, and it utilizes a visual programming language, grasshopper (Fig. 4). Some applications of grasshoppers were used for generating flocking agents (Quelea) and analyzing radiation simulation (Ladybug).

A. Kinetic Façade Design: Rotating Louvers

1) Kinetic Mechanism

The kinetic facade used in the experiments is a rotating vertical louver to control the opening and closing of the building. The size of a louver is 3m by 5m (one story high). Two servo motors attached at both ends of a louver drive power to the louver as actuators. The building is 20m in depth, 20m in length, and 45m (9 stories) in height and located on the hypothetical rotary in Inchon, Korea (latitude: 37.48°, longitude: 26.55°). Nearby buildings which have similar heights cast shadows on its façade surface. The curved facade is equipped with total 108 louvers.

2) Criteria

The kinetic façade, installed on the curtain wall as a double skin, controls radiation on the façade surface and openness to the outside as shown in Fig. 5. Each unit operates in response to one factor, taking into account the priority between radiation and openness. The radiation analysis needs both external and internal sensors while openness calculation need only internal sensors. Ladybug provides a radiation analysis component which is useful for calculating the energy collected on the building surface. However, it has limitations that do not take into account the reflection of sunlight. Radiation has priority to openness when it exceeds 0.20 kWh/m^2 for primary filtering of sensing points. Secondary filtering is conducted by remaining only 20% of the first filtered sensing points randomly. The louver which was selected by agents becomes perpendicular to the solar azimuth angle to prevent direct sunlight. The actuation does not reflect the sun altitude angle because it rotates about the vertical axis.

Other louvers are perpendicular to the facade surface to ensure maximum openness. The openness of each louver is the ratio of the area of each grid minus the projected area of the rotating louver.

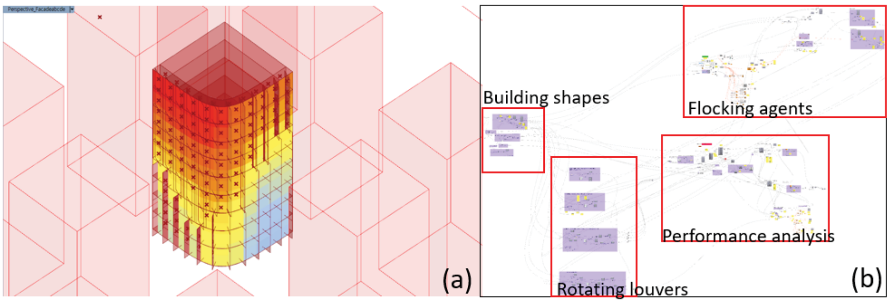


Fig. 4 (a) Rhino 3D and (b) grasshopper

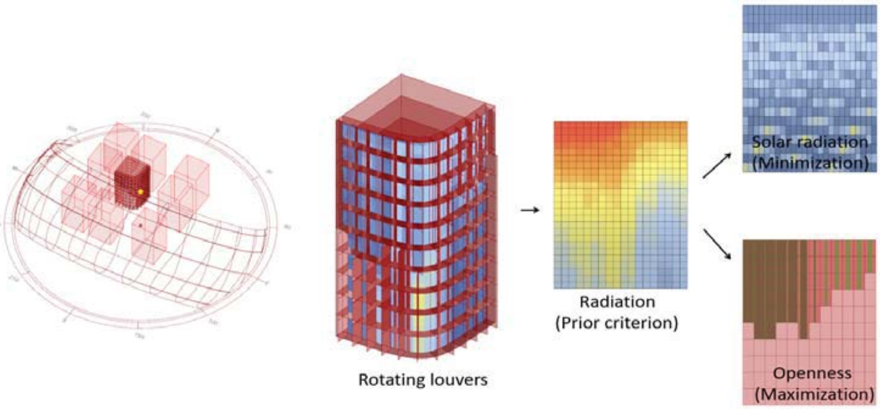


Fig. 5 Rotating louvers and multi-objectives

3) Flocking Algorithm

Flocking agents are emitted every time-step continuously on the random spot of the façade surface. The lifetime of each agent is set to twice the number of units responding to solar radiation, so the number of agents maintain constant until environmental conditions change. The details of agents are as shown in Table I.

TABLE I
AGENTS SETTING

Max speed	Max force	Vision radius (m)	Vision angle (°)
3	0.24	100	360

The details of the steering forces are as shown in Table II.

TABLE II
STEERING FORCE SETTING

Cohese force	Separate force	Align force	View force	Seek force
0	1	0	1	0.2

Based on above settings, the agents look for target points. Each louver operates when 8 or more agents are within 3 meters from each grid.

4) Comparison Group

The performance of FDC was assessed by comparing with the four other different control systems under the same condition (Fig. 6). A series of experiments measuring radiation and openness of them were conducted at 1-hour intervals from 9 to 16 on June 21, 2017 (the summer solstice).

The comparison group is as follows. Façade A is without any louvers. Façade B has fixed louvers perpendicular to the facade surface. In Façade C, every louver is perpendicular to solar azimuth angle (Centralized control). In Façade D, louvers in the reaction are perpendicular to solar azimuth angle. The others are perpendicular to the facade surface (Simple decentralized control). In other words, only primary filtering was applied. Façade E is for FDC. In case of Façade E, the number of agents is changing according to the period. So, average data from 100 time-steps were used after they became stable.

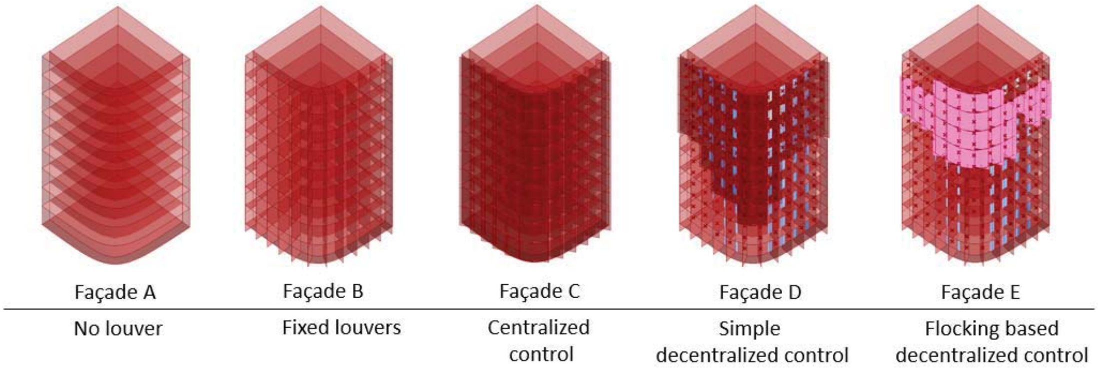


Fig. 6 Comparison group

V. RESULTS

A. Angle and Number of Louvers

Table III shows the angles of radiation-preferred louvers over time.

TABLE III
SOLAR VECTOR AND ANGLE OF LOUVERS

Time	Sun Altitudes (°)	Sun Azimuths (°)	AR (°)
9:00-10:00	42.14	91.03	1.03
10:00-11:00	53.96	101.66	11.66
11:00-12:00	65.18	117.65	27.65
12:00-13:00	74.01	148.96	58.96
13:00-14:00	75.01	202.13	112.13
14:00-15:00	67.11	238.12	148.12
15:00-16:00	56.13	255.92	165.92

AR=Angle of radiation-preferred louvers

Each façade has 108 louvers in total. Table IV shows the number of radiation-preferred and openness-preferred louvers. In Façade D and E, each number of radiation-preferred louvers increased the most at 13:00. The numbers of Facade E was from 46.8% to 68.13% of that of Façade D.

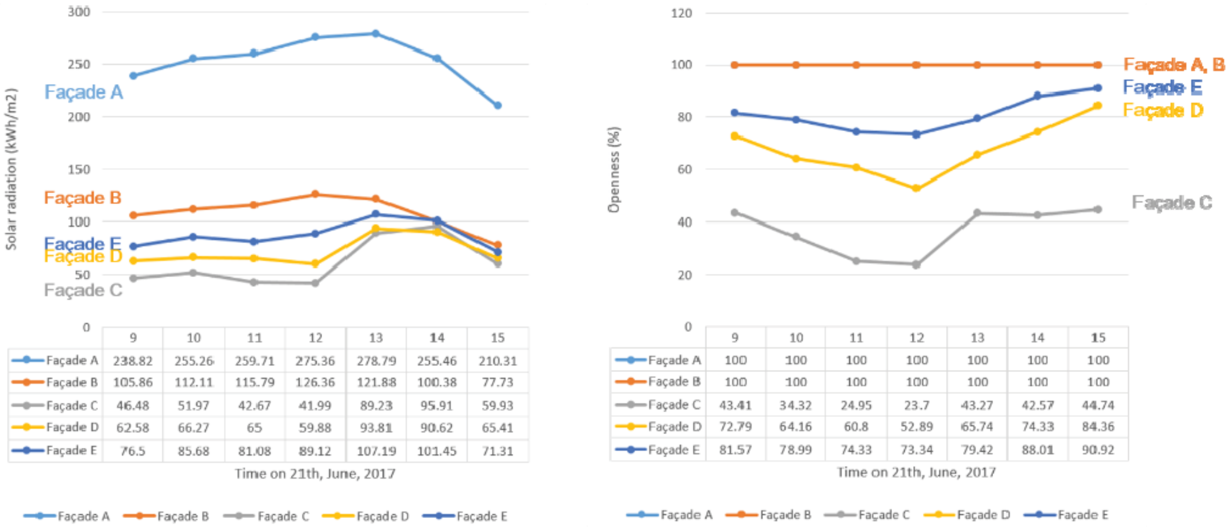
TABLE IV
NUMBER OF LOUVERS

Time	Façade A (R/O)	Façade B (R/O)	Façade C (R/O)	Façade D (R/O)	Façade E (R/O, Avg.)
9:00-10:00	0/0	0/108	108/0	46/62	31.34/76.66
10:00-11:00	0/0	0/108	108/0	55/53	34.23/73.77
11:00-12:00	0/0	0/108	108/0	55/53	36.66/71.34
12:00-13:00	0/0	0/108	108/0	61/47	36.87/71.13
13:00-14:00	0/0	0/108	108/0	62/46	38.32/69.68
14:00-15:00	0/0	0/108	108/0	54/54	25.31/82.69
15:00-16:00	0/0	0/108	108/0	40/68	21.87/86.13

R=Number of radiation-preferred louvers; O=Number of openness-preferred louvers

B. Sensor Values

Fig. 7 shows the internal sensor values on the curtain wall inside the rotating louvers over time. The three kinetic façades (Façade C, D, E) reduced more solar radiation than fixed louvers. Before 13:00, the more solar radiation reduced in order of Façade C, D, and E. It follows the number of the radiation preferred louvers. After 13:00, all three kinetic facades perform similar performance to that of Façade B. When it comes to the openness, Façade E showed the highest performance except for Façade A and Façade B with 100% openness.



	9	10	11	12	13	14	15
Façade A	238.82	255.26	259.71	275.36	278.79	255.46	210.31
Façade B	105.86	112.11	115.79	126.36	121.88	100.38	77.73
Façade C	46.48	51.97	42.67	41.99	89.23	95.91	59.93
Façade D	62.58	66.27	65	59.88	93.81	90.62	65.41
Façade E	76.5	85.68	81.08	89.12	107.19	101.45	71.31

Time on 21th, June, 2017

	9	10	11	12	13	14	15
Façade A	100	100	100	100	100	100	100
Façade B	100	100	100	100	100	100	100
Façade C	43.41	34.32	24.95	23.7	43.27	42.57	44.74
Façade D	72.79	64.16	60.8	52.89	65.74	74.33	84.36
Façade E	81.57	78.99	74.33	73.34	79.42	88.01	90.92

Time on 21th, June, 2017

Fig. 7 Internal sensor values: solar radaiation and openness

C. Assessment

The criteria were scored and their weighted averages were calculated to assess the performances of each Facade (A weight of radiation: 0.6, a weight of openness: 0.4). Radiation values were remapped into 0 to 100 by (1) like openness.

$$RS = \frac{FAR - R}{FAR} * 100 \tag{1}$$

where RS= Radiation score; FAR=Radiation of Façade A; R=radiation. Except for Façade A and Façade B with 100% of openness, Façade E's score was the highest among the three kinetic facades. In short, FDC achieved optimal performance in reducing radiation and maximizing openness.

TABLE V
SCORES AND WEIGHTED AVERAGES

Time	Façade C		Façade D		Façade E	
	R	S	R	S	R	S
9:00-10:00	80.53	43.41	73.79	72.79	67.96	81.57
10:00-11:00	79.64	34.32	74.03	64.16	66.43	78.99
11:00-12:00	83.57	24.95	74.97	60.80	68.78	74.33
12:00-13:00	84.75	23.7	78.25	52.89	67.63	73.34
13:00-14:00	67.99	43.27	66.35	65.74	61.55	79.42
14:00-15:00	62.45	42.57	64.52	74.33	60.28	88.01
15:00-16:00	71.50	44.74	68.89	84.36	66.09	90.92
Avg.	75.77	36.70	71.54	67.86	65.53	80.94
Weight	0.6	0.4	0.6	0.4	0.6	0.4
Weighted Avg.	60.15		70.07		71.69	

RS=Radiation score; OS=Openness score.

VI. DISCUSSION

The average and standard deviation of the number of the radiation preferred louver show the stability of the control of Façade E which is controlled by agents. The standard deviation, which was less than 3, increased sharply since 14:00. Its change tendency corresponded to that of the standard deviation of solar radiation. In other words, the high standard deviation means that the agents could not control the façade with stability.

TABLE VI
RESULTS OF FAÇADE E

Time	A	R		Radiation (kWh/m2)		Openness (%)	
		Avg.	SD	Avg.	SD	Avg.	SD
9:00-10:00	115	31.34	2.57	76.50	3.34	81.57	1.53
10:00-11:00	135	34.23	1.77	85.68	3.19	78.99	1.28
11:00-12:00	139	36.66	2.49	81.08	3.51	74.33	1.99
12:00-13:00	159	36.87	2.97	89.12	4.22	73.34	2.16
13:00-14:00	163	38.32	2.85	107.19	3.28	79.42	1.75
14:00-15:00	141	25.31	5.93	101.45	5.2	88.01	2.86
15:00-16:00	97	21.87	3.76	71.31	2.11	90.92	3.55

A=Number of flocking agents; R=Number of radiation-preferred louvers.

The shape of the reaction zone explains the reason. After 14:00, it was asymmetric compared to that of before 14:00. In the asymmetric zone, the agents had difficulty changing their movements as the target points were located on one side. In the symmetric reaction zone, on the other hand, the agents' mobility got higher because the most of the target points emerged around the middle of the façade surface.

VII. CONCLUSION

This study presents a biomimetic methodology for designing kinetic patterns of a kinetic facade. Flocking based decentralized control (FDC) utilizes agents moving autonomously on the façade surface. A series of experiments verified that FDC performs multi-objective optimizations (Solar radiation and openness). FDC tend to degrade when the shape of the reaction zone was asymmetric.

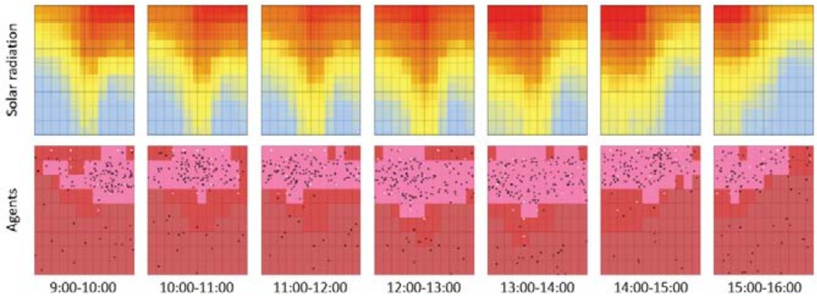


Fig. 8 The shape of reaction zones

There are two implications of this study: the beauty of nature and convergence. The biomimetic approach not only solves the functional problem but also interact with nature. It enables a kinetic façade to show material improvisation on site [14]. Today, all phases of design and construction are being integrated in real time based on computational tools, collaborative work processes, and the cloud [15]. In other words, designers can conduct a performance-oriented design process with a rough idea from the early design phase.

This paper has some limitations and requires future works. First, solar radiation made only one reaction zone because it did not change drastically. It is necessary to simulate discontinuous and complex criteria so that FDC can cover multiple reaction zones flexibly. Second, all the movements of façade were pre-set according to the condition. The number of agents just determined whether each unit react to solar vector or not. If each unit can be controlled by the number, more sensitive control is possible for the optimization of performance.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2016R1D1 A1B01013694).

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