GENERATION OF DIVERSE DYNAMIC BEHAVIORS USING THE EMERGENT DESIGN SYSTEM

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Herein we examined the first step for constructing an emergent design system capable of generating diverse behaviors. We proposed method to generate diverse dynamic behaviors. The form generation method in the emergent design system initially generated diverse two-dimensional forms, and forms with various features were then produced by changing the composite ratio k, which is a system parameter. Then these forms were converted into two-dimensional mass point systems composed of mass points, springs, and dampers. The behaviors of the two-dimensional mass point systems were analyzed by the Runge-Kutta method to examine the effects of applying external forces such as loads and vibrations on the various behaviors such as rotational movement. Our results indicated that diverse forms with different displacement tracks of the center of gravity are also generated under the same mechanical conditions.

Keywords: Dynamic behaviors, Diversity, Emergence.

1. INTRODUCTION

In the early process of design, the design objective and constraint conditions are unclear compared to the late process of design. Thus, a global solution search is needed. The emergent design system, which can generate diverse shapes under unclear design conditions, has been proposed as a global search method for the early process of design [1]. To demonstrate the effectiveness in yielding diverse solutions, the emergent design system has been applied to the design of an artificial hip stem and a car body frame [2, 3]. However, the objective in these cases was to create diverse structures, and did not consider active movements, including machine elements such as dampers and actuators. In recent years, the number of design objects considering both structure and dynamic behavior, e.g. robotics, has increased. For example, the use and work content of robots have diversified from mundane jobs such as working on assembly lines in factories to life assistance in human society. Moreover, the environments where artifacts are used will be extended in the near future as artifacts with dynamic behaviors become more commonplace. Therefore, if the emergent design system can be expanded into a design system capable of generating dynamic behaviors, the design environment will be improved. Additionally, the emergent design system may realize the creation of artificial life that adjusts to diverse environments.

From these perspectives, this study aims to construct an emergent design system capable of generating diverse forms and dynamic behaviors. To this end, we propose a basic method to generate dynamic behavior, and demonstrate that diverse dynamic behaviors are generated using the proposed method. This method first generates diverse two-dimensional forms using the form generation method in the emergent design system. Then the generated forms are converted into two-dimensional mass point systems, which are constructed by mass points, springs, and dampers. Finally, the behavior, which is generated by an external force, is analyzed using a numerical analysis method.

Research into Design — Supporting Sustainable Product Development. *Edited by* Amaresh Chakrabarti
 Published by Research Publishing
ISBN: 978-981-08-7721-7

2. EMERGENT DESIGN SYSTEM

2.1. Concept of emergence and emergent design

In nature, various organisms exist in the same environment. In the fields of biology and ecology, scientists have hypothesized that various species have been created through the process of emergence. According to Kitamura [4], emergence is defined as a new function, character, and action acquired by an interactive dynamic process where global order appears through local interactions between individuals behaving autonomously with the environment. On the other hand, this order restrains the behavior of an individual. Thus, the appearance of global order is a bottom-up process, whereas the process of restraining individual behavior is a top-down process. By comparing the design process proposed herein to the emergence process, the following similarities are observed. First, the process to generate a design proposal by evaluating certain standards is similar to the bottom-up process to generate the entire feature by the interaction of autonomous components in emergence. Second, the process to optimize specific components of the design proposal is similar to the top-down process, which binds the components by the entire feature in emergence. Thus, the concept of emergence may be applicable to design, and diverse novel design solution candidates can be derived by "emergent design" where the bottom-up and top-down processes interact [5].

2.2. Outline of the emergent design system

The emergent design system proposed herein is based on the emergent design described above [1]. The emergent design system is composed of two processes. The bottom-up process generates a diverse three-dimensional form, while the top-down process optimizes the form obtained in the bottom-up process (The explanation of top-down process is transferred to the paper [1, 2].).

The bottom-up process generates diverse forms by cellular automata (CA). The element of CA is expressed by the voxel in this system. Moreover, induction and apical dominance, which are generation characteristics originating in biodiversity as a state transition rule in CA, are introduced, and are described below.

- Induction

Induction is a generation characteristic, which changes a neighboring cell to a specific character, and influences the activation of cell proliferation by the action of a cell on neighboring cells (Figure 1). Thus, a certain element provides a stimulus, which influences the generation of a neighboring element. This can be modeled as the neighboring information vector, which is expressed as

$$v_n = \sum_{i=1}^{26} b_i w_i e_i \tag{1}$$

where n is the number of maximum surrounding elements. i is the surrounding element number. b_i indicates the existence or non-existence of an element (1 or 0, respectively), and w_i is the size of the induction action recorded in a one-dimensional arrangement created when each form is generated and has a value ranging from 0 to 8. $\boldsymbol{e}_i$ is the unit vector of the direction to the object element.

- Apical dominance

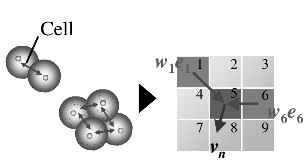


Figure 1. Induction.

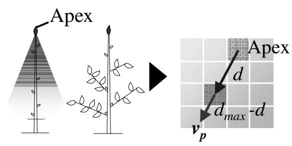


Figure 2. Apical dominance.

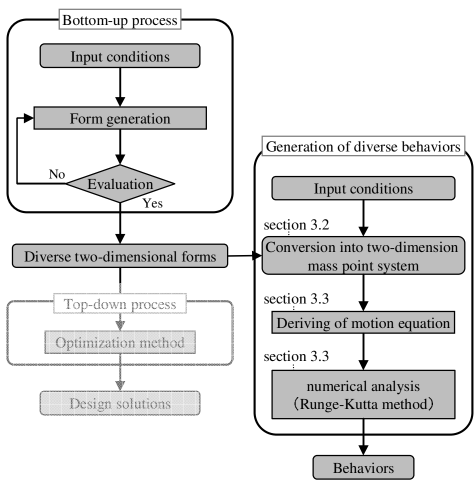


Figure 3. Flow chart of a generation method.

Apical dominance is a generation characteristic, which predominately manages the ontogeny, also referred to as the apex, influences the morphogenesis, and controls cell proliferation (Figure 2). This predominant action increases when the apex distance is short. For example, if a plant has the apex in the position shown in Figure 3, then leaf growth is controlled from the apex. Consequently, light can be efficiently received. The positional information vector, which is influenced by relationship of the apex to the object element, can be modeled from the aforementioned character as

$$v_p = (d_{\max} - d)\, e_d \tag{2}$$

where $d_{\max}$ is the distance between the apex and the most distant cell from the apex. d is the distance between the apex and the object element, and $\boldsymbol{e}_d$ is the unit vector of the direction to the object element. By uniting these two vectors, the composite ratio can be defined as k, and the input vector of CA becomes

$$v_{in} = k\, v_n + (1 - k)\, v_p \tag{3}$$

If k has a value near unity, then induction tends to strongly influence k. In contrast, k near 0 is strongly influenced by apical dominance, which tends to generate a rhabdoid form or board form. The input parameters in the bottom-up process are the apex position, composite ratio k, shape generation space, element size, initial element, and evaluation item. The apex position becomes the center of the action for apical dominance, and the form generation space is a space allowing CA to be generated. The element size is the voxel size, which composes form, and reducing the element size causes the output to be in a detailed form. The initial element position is where the shape generation of CA is initiated. Thus, it is possible for an element to have two or more components and for the part where the element definitely exists in the design to be assumed as the initial element. The generation number is the frequency that the form is updated. Furthermore, the bottom-up process must satisfy the evaluation item.

3. GENERATION METHOD FOR DYNAMIC BEHAVIORS

3.1. Outline of the generation method for dynamic behaviors

Figure 3 shows the flowchart for the generation method for diverse dynamic behaviors. First, two-dimensional shapes are generated using the bottom-up process of the emergent design system. Then these shapes are converted into two-dimensional mass point systems where the generated shape is connected with dampers and springs. Next, the behaviors of these shapes are analyzed by solving the equation of motion for the converted two-dimensional mass point system. Section 3.2 describes the modeling method for the two-dimensional mass point system, while the behavior analysis method is described in Section 3.3.

3.2. Conversion into a two-dimensional mass point system

The generated shape is converted into a two-dimensional mass point system as follows. First, a mass point is assumed to exist in the center of the element of the generated shape (Figure 4(b)). Next, the mass points, which exist in eight directions, are connected with dampers and springs. Moreover, the connection of the restraint side and mass point is assumed to attach all the springs and dampers. For instance, as shown in Figure 4(c), when the bottom is a restraint side, a mass point attached to the bottom connects all the springs and dampers that can be connected to the bottom.

3.3. Behavior analysis method

The external force and constraint condition are set after analyzing the behavior of a shape converted into the two-dimensional mass point system, and the motion equation of each mass point is derived. In this case, Figure 5 shows springs and dampers connected to each mass point. Because eight or less pieces are connected to the length and diagonal sides, springs and dampers can model the motion equation for one mass point. Moreover, because eight springs and dampers are connected to one mass point in the horizontal direction, the vertical direction, and the diagonal in the maximum case, the motion equation can be expressed as

$$m\frac{d^2}{dt^2}r_{ij} = b_{ij}f_{\mathrm{ext}ij} + \sum_{x=i-1}^{i+1}\sum_{y=j-1}^{j+1} a_{xy}f_{xy} - a_{ij}f_{ij} \quad (4)$$

where m is the mass of a mass point, and r_{ij} is the positional vector of mass point $[i,j]$. a_{ij} indicates the existence or non-existence of a mass point (1 or 0, respectively), whereas b_{ij} indicates the existence or

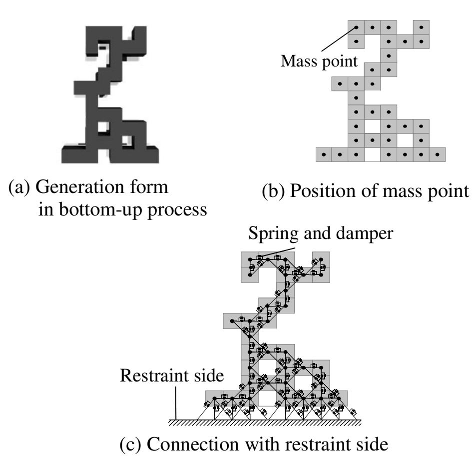


Figure 4. Conversion into two-dimension mass point system.

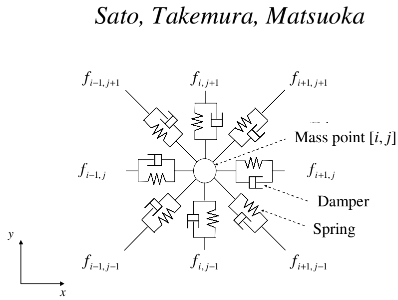


Figure 5. Forces to act on mass point.

non-existence of an external force acting on mass point $[i,j]$ (1 or 0, respectively). $\boldsymbol{f}_{\mathbf{ext}ij}$ is an external force to a mass point $[i,j]$, and $\boldsymbol{f}_{ij}$ is the resultant force of the elastic force and damping force acting on mass point $[i,j]$. Thus, the behavior of a two-dimensional mass point system can be analyzed by solving this motion equation. The Runge-Kutta method [6], which employs an easy computational method to solve the motion equation of expression (4), can give the displacement, velocity, and acceleration of shape with time.

4. EXECUTION OF BEHAVIOR GENERATION

4.1. Generation of shape and conversion into a two-dimensional mass point system

First, the value of composite ratio k is changed from 0.1 to 0.9 at 0.1 intervals, and shape generation is executed by the bottom-up process of the emergent design system. The shape generation space is initially a square with 10 elements per side. Figure 6 shows an example of the shape generation process. The two-dimensional shape is self-organizationally generated. Moreover, the example of shapes generated from each composite ratio (Figure 7) indicates the following features. As the composite ratio becomes smaller, the number of elements in the generated shape decreases, and shapes like a skeleton are produced. In contrast, as the composite ratio becomes larger, there are more elements in the generated shape, producing massive shapes. These shapes are then converted into two-dimensional mass point systems by assuming the element of the generated shape has mass in the center, as described in Section 3.2, and connecting the mass with springs and dampers. Figure 8 shows an example of a two-dimensional mass point system, and confirms that the generated shape can be converted into a mass point system comprised of a mass point, springs, and dampers.

4.2. Behavior generation using a two-dimensional mass point system

In this study, the behaviors of each two-dimensional mass system are generated under each mechanical condition of loading and vibration.

4.2.1. Behavior generation with vibration

Loading is set as a mechanical condition, and the behaviors of the two-dimensional mass point system are generated. Table 3.1. show the analysis condition where each parameter contains a machine

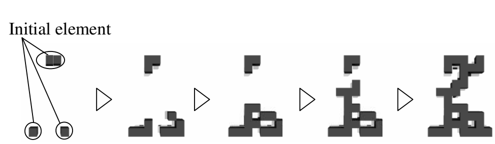
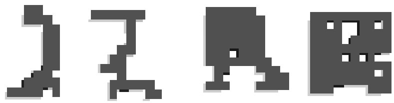
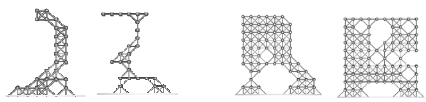


Figure 6. Shape generation process.



(a) k=0.2 (b) k=0.8

Figure 7. Examples of generated shapes.



(a) k=0.2 (b) k=0.8

Figure 8. Examples of two-dimension mass point system.

Table 1. Analysis conditions.

Mass	0.001 kg
Spring constant	0.1 N/m
Damping constant	0.03 kg/s
Distance between mass point	0.1 m

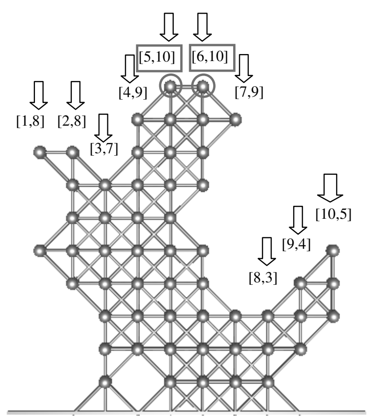


Figure 9. Loading condition.

element composed of a two-dimensional mass point system. The loading conditions are assumed to be weighted to mass point whose value of y coordinate is the largest in each x coordinate value (Figure 9). Additionally, the external force, which gradually increases the size of the load with time, is assigned to each mass. Because a large deformation was expected, the endurance load is assumed to be the analytical end condition, and is ±35% of the natural length of the springs and dampers; the endurance load is the load when either the mass becomes $y < 0$ or the springs and dampers exceed the range of movement. Thus, the endurance load and displacement of the center of gravity by the load are evaluation items for behavior.

Figure 10 shows the results of behavior generation for an example of a two-dimensional mass point system. When each load point is given a proportional external force, the mass point is located under the hem. Loading was confirmed to reach the endurance load. Figure 11 depicts the relationship between additional loading and the x, y displacement of the center of gravity in a two-dimensional mass point system. The displacement tracks of the center of gravity for each load differ under the same load

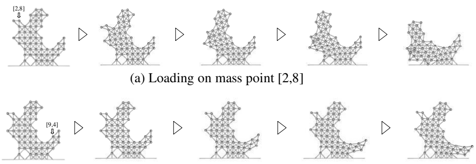
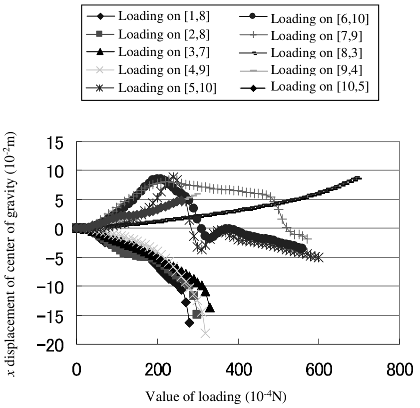
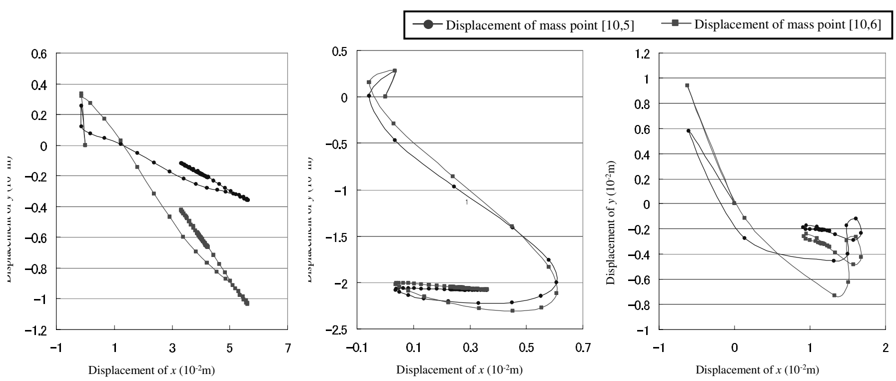


Figure 10. Example of behavior.



(a) Value loading and *x* displacement (b) Value loading and *y* displacement

Figure 11. Rerationship of displacement of center of gravity and loading.



(a) Vibration frequency = 1Hz, Spring constant = 0.1N/m (b) Vibration frequency = 5Hz, Spring constant = 0.1N/m (c) Vibration frequency = 1Hz, Spring constant = 1.0N/m

Figure 12. Tracks of mass point [10, 5] [10, 6] by vibration.

condition. Figures 11(a) and 11(b) confirm that various behaviors are generated. Additionally, the *x* displacement of the center of gravity significantly changes even when the displacement is weighted in the *y* direction. Moreover, the shape is also a factor in the rotational motion, which centered around a specific location, as well as the positive or negative change in displacement by the load point. The value of the endurance load differs for each load point. Symmetric shapes or mass points arranged under a load point tend to exhibit a high endurance.

4.2.2. Behavior generation with vibration

Next, the bottom of a shape is vibrated to generate the behavior of the two-dimensional mass point system. The time change of mass points [5, 10] and [6, 10], which are set as initial elements, is assumed to be a behavior characteristic. Figure 12(a) shows the tracks of mass points [6, 10] and [5, 10] when the given vibration is a longitudinal vibration with an amplitude of 0.05 m and an axial vibration frequency of 1 Hz. Figures 12(b) and 12(c) show the behaviors when the vibration frequency and spring constant are changed. Each mass point displays a similar behavior because the mass is adjoined even if the spring constant is changed. However, changing the spring constant and vibration frequency induces an entirely different behavior. Thus, a small difference in the spring constant and the position of an individual mass point greatly influences the behavior on the whole.

5. DIVERSITY OF THE GENERATED BEHAVIOR

5.1. Comparison of each behavior characteristics by generated shapes from the emergent design system with the fundamental shapes

Items in each mechanical condition are set to evaluate the effects of the loading and vibration on the diversity of the generated behavior. The value and the x, y displacement of the center of gravity of the endurance load are evaluation items for loading, whereas the x, y displacement of mass point[10, 6] is used for vibration. In addition, the fundamental forms (69 total, Figure 13), are compared to the behavior characteristics of the generated shapes using the emergent design system. Figure 14 is a scatter chart of the shapes generated for each behavior characteristic where the vertical and horizontal axes shows the behavior characteristic for loading and vibration, respectively. Moreover, the square plot shows the two-dimensional mass point system generated using the emergent design system, while the circular plot denotes the fundamental form. The results confirm that behavior characteristics for the shape generated using the emergent design system are more diverse. Symmetry may make it difficult to easily move the shape in the fundamental form. Moreover, the endurance load is indicated a high value because a force is distributed to more springs and dampers when the external force is present.

5.2. Comparison of the shape for each composite ratio k

The relation between behavior diversity and the composite ratio k, which is a system parameter when a shape is generated with the emergence design system, is analyzed. The value of the composite

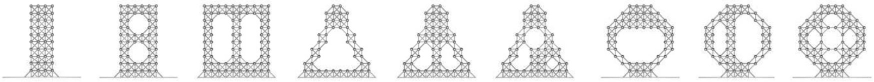


Figure 13. Examples of fundamental shapes.

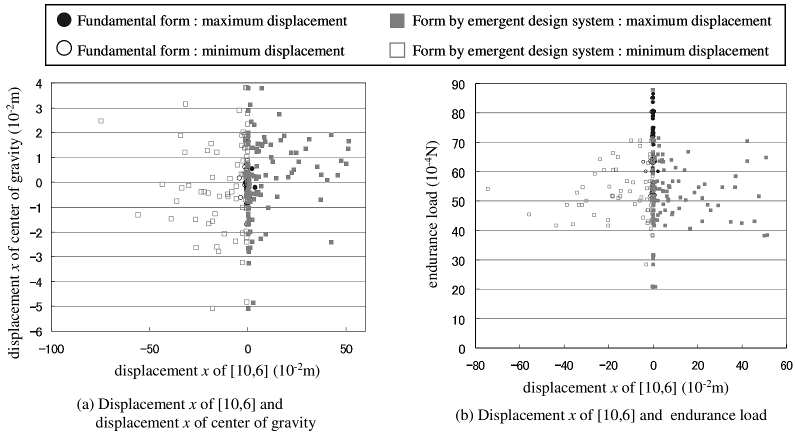


Figure 14. Comparison between fundamental forms and generated shapes with composite ratio $k(= 0.5)$.

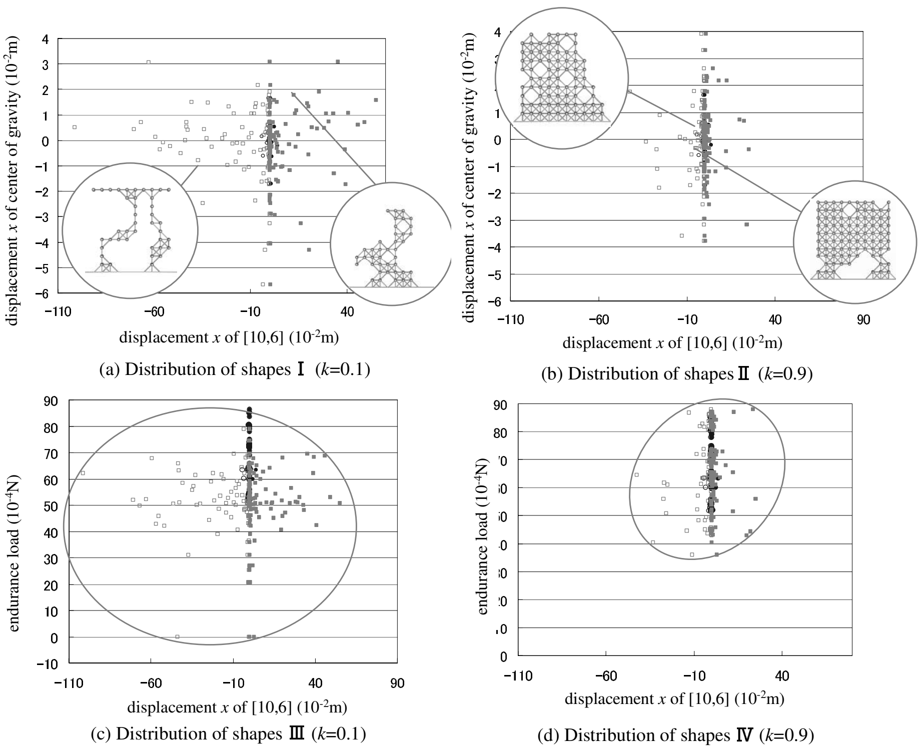


Figure 15. Diversity of behavior in each composite ratio.

ratio *k* varied from 0.1 to 0.9 at 0.1 intervals, and shape generation was executed. Figure 15 shows the distribution of a two-dimensional mass point system for each composite ratio *k* by the behavior characteristic. As the displacement *x* and *y* for the center of gravity for a shape with a composite ratio increases, behavior diversity increases, and the endurance load tends to have a low value. On the other hand, the behavior diversity decreases for a shape with a high composite ratio because the displacement value decreases, and the endurance load tends to have a high value.

Because shapes easily become like a skeleton when the composite ratio is low, behaviors should grow readily. Therefore, the value of the endurance load should decrease as the displacement of a mass point increases and when a mass point is located under the base. In contrast, the displacement of the mass point decreases because shapes with high composite ratios tend to be massive, which reduces behavior diversity. However, the endurance load has a high value because the probability of mass being located on the base decreases and the load can be distributed by an external force. Hence, shapes with a low displacement due to loading and vibration tend to be easily generated with a high composite ratio *k* (e.g. 0.9), whereas diverse behaviors with low or high displacements with loading and vibration, respectively, tend to be generated with a low composite ratio *k* (e.g. 0.1).

6. CONCLUSIONS

This study developed the first step to construct an emergent design system capable of generating diverse behaviors. Shapes, which were generated using the bottom-up process of the emergent design system, were converted into a two-dimensional mass point system composed of mass points, springs, and dampers. Then the behavior was analyzed. The results of this research are summarized below.

1. A method to convert shapes into a two-dimensional mass point system and an analysis method for the behavior of this system are demonstrated.

2. Comparing the behavior characteristics of the external force for each shape to the fundamental forms confirmed that the shapes generated by this system have various values for each characteristic and exhibit diverse behaviors.
3. Shapes, which show a low displacement with the external force, are easily generated when the composite ratio is high as a consequence of changing the composite ratio k, which is a parameter of the emergent design system. Moreover, diverse shapes, which show a low displacement or high displacement to the external force, are generated by setting the composite ratio k to a low value.

In future works, we intend to examine behavior generation for the best behavior and to expand the shape generation space for a given condition by introducing a top-down process.

ACKNOWLEDGMENTS

This work was supported in part by Grant in Aid for the Global Center of Excellence Program for "Center for Education and Research of Symbiotic, Safe and Secure System Design" from the Ministry of Education, Culture, Sport, and Technology in Japan.

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