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Multi-Objective Optimization of Spatial Truss Structures by Genetic Algorithm

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Abstract. In this paper, architectural constructions composed of spatial truss units are considered by using a new technique of artificial life. Such spatial truss structure has flexibility and adaptability to environments. At first, equilateral tetrahedral (regular tetrahedral) units, which are basic space units having three dimensions, are proliferated to specified directions at random. At every proliferation step, various architectural evaluations and selections are performed according to obtained degrees of adaptation to environments. The purpose of this paper is to compose a system for a variety of automatical formation, which satisfies the given architectural and environmental conditions by using Genetic Algorithm (GA) originated by HOLLAND and GOLDBERG. The effectiveness of the proposed system is shown by digital and graphical simulations.

1. Introduction

Architectural structures exist between human lives and natural environments. Therefore they should be designed under many kinds of conditions, such as safety, economy and harmonization with environments. In such a design, intelligent systems, e.g., artificial intelligence, fuzzy theory and artificial life are considered to be useful.

In this paper, architectural constructions composed of spatial truss units are considered by using a new technique of artificial life, so that they are adaptable to internal or external demands and to the given conditions. At designing of architectural structures, there exist various objective and contradictory conditions. Therefore, it is necessary to employ multi-objective optimization methods. Spatial truss structures having high flexibilities are employed from the viewpoint of internal or external environmental adaptabilities in this research. Especially geographic and static conditions are taken into account. The purpose is to present a multi-objective optimal formation system for various types of spatial truss structures by applying Genetic Algorithm (GA) originated by HOLLAND (1975) and GOLDBERG (1989). As for multi-objective evaluation functions for GA, Fuzzy Theory originated by ZADEH (1965) is introduced because of its simplicity and adaptability to every kind of the given constraints and goals.

2. Formation System by GA

2.1. Outline

Equilateral tetrahedral (regular tetrahedral) units, which are basic space units having three dimensions, are assumed to be proliferated to neighboring spatial positions according to a genetic code (G-type). At every proliferation step, various architectural evaluations are performed, and degrees of the adaptation to the given conditions are obtained automatically. The following five evaluations are employed; (1)Stability, (2) Efficiency of the floor space, (3) Position of units on a slope, (4) Allowable tensile stress of structural members, and (5) Buckling load. The evaluations of (1), (4), and (5) are given from the structural point of view. The evaluation (2) is demanded at architectural planning. The evaluation (3) is applied to slopes which is adapted to geographic conditions. In Japan there are many slopes and the effective use of slopes is considered to be an important problem. Therefore, in this paper, a sloping area is employed as a site. A form taken higher evaluations than others is allowed to survive. By crossing G-types of the survived forms, a new form at the next generation is born. These operations are repeated a hundred times. A form getting the highest evaluations at all generations is considered to be the most suitable one.

In this system, an equilateral tetrahedron cell is regarded as a unit, and its proliferation in accordance with a G-type forms the spatial truss structure. Figure 1 shows a flowchart of this system. A structure having a high adaptation degree by this system is formed. Fundamental assumptions employed in this paper are as follows:

(a) 20 G-types are produced by the decimal numbers of 1–12 at random. This group of G-type is the First group. The proliferation times of each individual are 40.

(b) Structures are formed by the proliferation that is complied with each G-type, and each structure is evaluated by the evaluation functions as shown in Subsec. 2.3.

(c) Only 6 individuals that have the higher adaptation degrees than others survive out

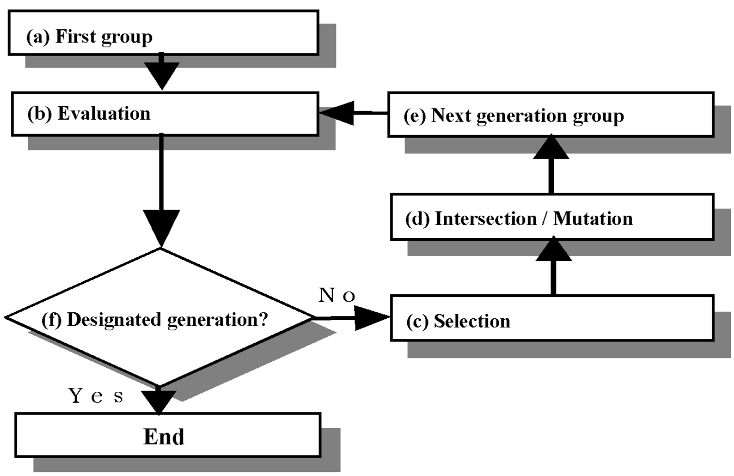


Fig. 1. Flowchart of a system by GA.

at the same generation and the other individuals are eliminated.

(d) The genetic operations such as intersection/mutation are carried out to 6 individuals which are survived. The process of the intersection and mutation is shown in Subsec. 2.2.

(e) 30 individuals are generated by each intersection of the above mentioned 6 individuals. These 30 individuals belong to the next generation group.

(f) The terminative condition is assumed that the generation reaches 100.

2.2. Creation of forms by GA

In this system, the equilateral tetrahedron is a basic unit and three-dimensional structures are formed by the proliferation of the unit. The proliferation is performed in accordance with each G-type as shown in Fig. 2. A G-type is composed of 1–12 numbers. Each number through 1 to 12 shows the direction of the proliferation (Fig. 3). In Fig. 3, the central deep colored solid unit is the original proliferation unit. In the G-type, the order of the figure is expressing the order of a proliferation, and the length of a G-type is expressing the total number of the proliferation. Each form is coded by this G-type. Figure 4 shows an example of the process of the 3 times proliferation. In accordance with this method, a three-dimensional structure is formed.

The genetic operations such as the intersection and the mutation are carried out to this G-type. The methods of the intersection and the mutation are shown in Figs. 5 and 6, respectively.

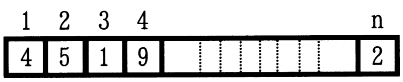


Fig. 2. Example of a G-type.

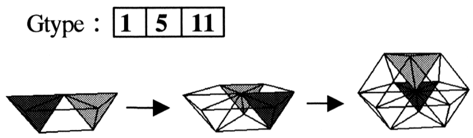


Fig. 4. Example of process of a proliferation.

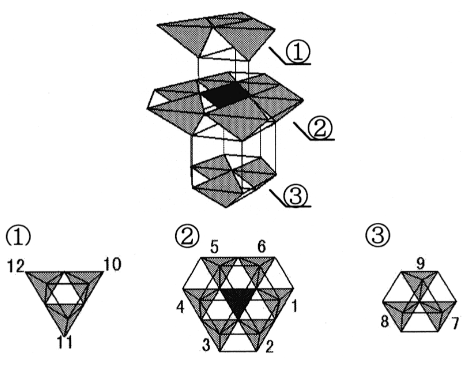


Fig. 3. Direction of a proliferation.

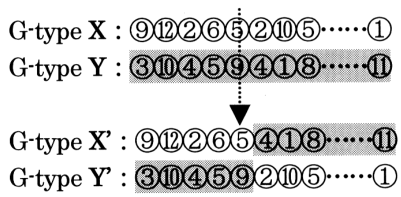


Fig. 5. Intersection.

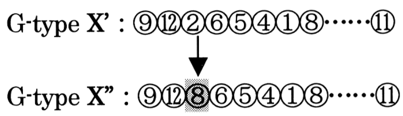


Fig. 6. Mutation.

2.3. Evaluations

By applying various evaluations to an individual structure, adaptation degrees of the structure are obtained in the given condition. Five kinds of evaluations are employed in this system and the functions are described with Fuzzy membership functions as shown in Fig. 7.

(1) Stability (Fig. 7(a))

The distances between the centers of the gravity (***Gx*** and ***Gy***) and the edges of structures touched to the ground (***dx*** and ***dy***) are evaluated. In the case that the center of gravity comes out the base of the structure, the adaptation degree is assumed to be 0, because of the possibility of the turnover.

(2) Efficiency of a floor space (Fig. 7(b))

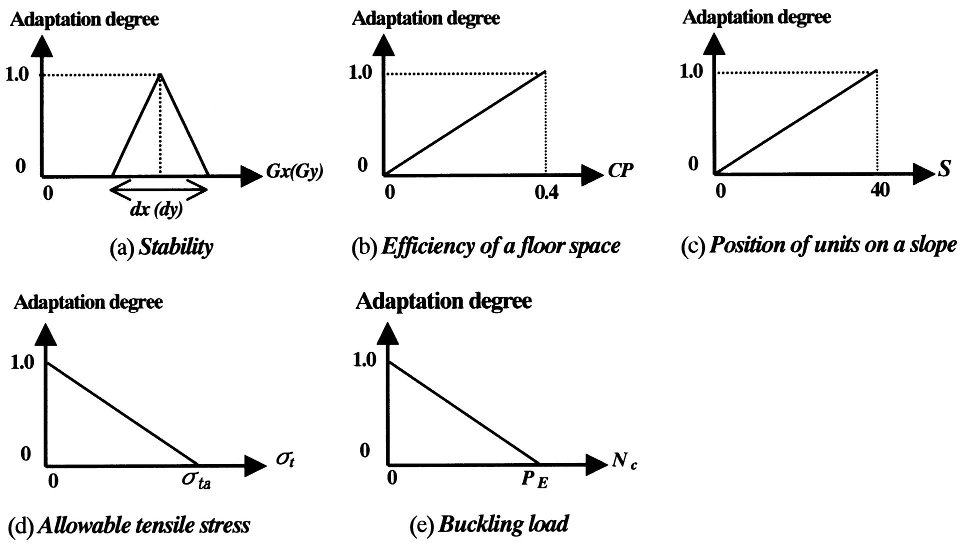
The ratio (***CP***) of the total area of floors to the total number of the members of structures is evaluated. This evaluation is employed because it is considered to be highly economical when a large floor area is obtained by a small number of structural members in the viewpoint of architectural planning. This evaluation has the following characteristics; (1) the shapes which continue in a certain direction can be avoided, (2) the units are concentrated in a certain floor level.

(3) Position of units on a slope (Fig. 7(c))

In this paper, a sloping area is employed as a site. To evaluate the effective use of this area, the ratio of the number of the units (***S***) which are in the sloping area to that of the total units is employed. As the number (***S***) of the units that exist in the space on the slope is large, the adaptation degree is high.

(4) Allowable tensile stress (Fig. 7(d))

In this system, static structural analyses are carried out under sustained loadings. The axial forces in each member are calculated. The tensile stress (σ_t) is calculated by the axial



Figs. 7. Evaluation functions.

force. The ratio of σ_t to the allowable tensile stress (σ_{ta}) is evaluated. When σ_t exceeds σ_{ta}, the adaptation degree is assumed to be 0.

(5) Buckling load (Fig. 7(e))

Compressive loads (N_c) are also obtained by a static structural analysis. The ratio of N_c to the buckling load (P_E) is evaluated. When N_c exceeds P_E, the adaptation degree is assumed to be 0.

(6) Total adaptation degree

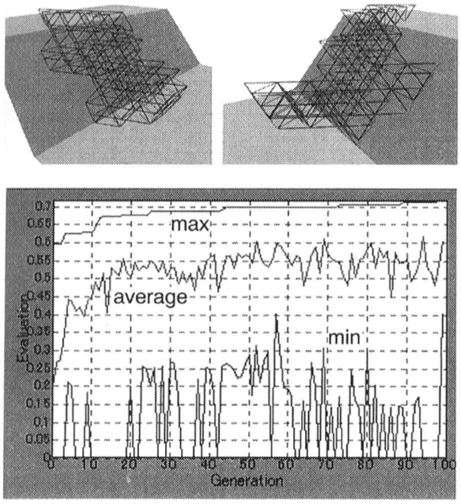
Each G-type is evaluated by the 5 kinds of evaluations mentioned above. The total adaptation degree (μ) of each individual is calculated by Eq. (1). Here, μ_1~μ_5 are the adaptation degrees of evaluations (1)~(5). The values of these coefficients a~e show the weights on each evaluation. Users can be operated in accordance with these coefficients.

$$\mu = \frac{a \times \mu_1 + b \times \mu_2 + c \times \mu_3 + d \times \mu_4 + e \times \mu_5}{a + b + c + d + e}. \qquad (1)$$

3. Results and Discussions

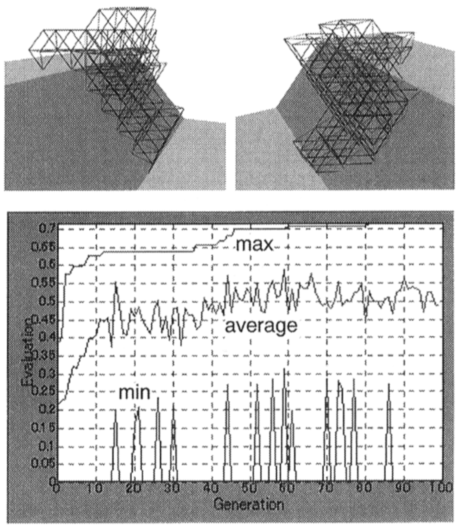
In this system, users can recognize the obtained final form because users can operate the viewpoint arbitrarily by using the 3-D graphical presentation method visually and interactively. (1)~(6) in Figs. 8–13 are the adaptation degrees of the 5 kinds of evaluations of *Stability*, *Efficiency of a floor space*, *Position of units on a slope*, *Allowable tensile stress*, and *Buckling load*, and (6) is the total adaptation degree.

Figures 8 and 9 show examples of the results in case that the values of all coefficients (a~e) are assumed to be 1. Though the assumed values of coefficients a~e are same, the



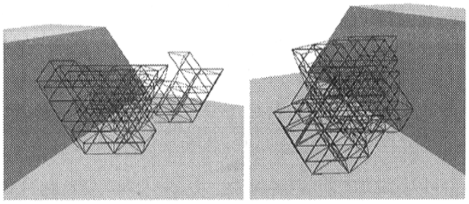
①0.686 ②0.620 ③0.891 ④0.750 ⑤0.606 ⑥0.714

Fig. 8. Example 1.



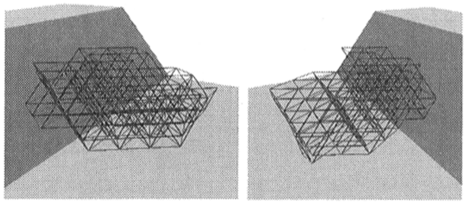
①0.798 ②0.708 ③0.707 ④0.735 ⑤0.602 ⑥0.717

Fig. 9. Example 2.



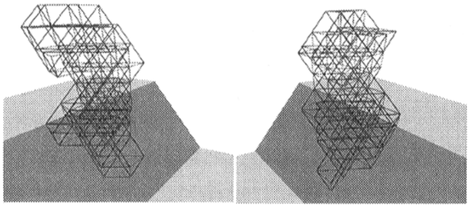
①0.977 ②0.678 ③0.225
④0.925 ⑤0.842 ⑥0.901
$a = 10$, b, c, d, and $e = 1$

Fig. 10. Stability.



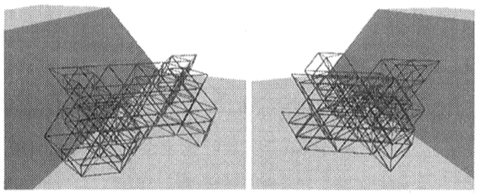
①0.985 ②0.793 ③0.152
④0.933 ⑤0.792 ⑥0.777
$b = 10$, a, c, d, and $e = 1$

Fig. 11. Efficiency of a floor space.



①0.000 ②0.591 ③0.999
④0.717 ⑤0.535 ⑥0.854
$c = 10$, a, b, d, and $e = 1$

Fig. 12. Position of units on a slope.



①0.925 ②0.645 ③0.200
④0.959 ⑤0.862 ⑥0.869
d and $e = 10$, a, b, and $c = 1$

Fig. 13. Allowable tensile stress/ Buckling load.

shape of the final forms are different. These differences depend on these of the G-type in the first group. Therefore, this result is considered to be insufficient from the viewpoint of the optimization. However, this result also shows a possibility to obtain various kinds of shapes. It is considered that these variations are natural and desirable because the optimal structural form is not always one. In Figs. 8 and 9, the changes of the total adaptation degrees, i.e., maximal, mean and minimal ones, are also shown.

Figures10–13 show the examples of simulation results, in case of that the value of the coefficient of the target evaluation is assumed to be 10 and those of other evaluations are to be 0. Various structural forms are obtained in accordance with the assumed coefficients. These results show that the final structural forms are influenced by the target evaluations, i.e., the assumed coefficients, and structural formations under subjective judgments of users are possible to be controlled by these values.

4. Conclusions

In this study, by using Genetic Algorithm (GA) and Fuzzy Theory, a great possibility of the multi-objective optimal formation systems for space truss structures is shown. The special merit that we can take into account human, social and environmental constraints and goals at designing of architectures by means of this system. However, the global ecosystem including architectures in the real world is not so simple. Therefore, further examinations are necessary. Especially, co-relationship among plural architectures should be considered based on complex systems in the future (YAMABE *et al*., 1998).

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