A Digital Prototyping System for Designing Novel 3D Geometries

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A Digital Prototyping System for Designing Novel 3D Geometries

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Abstract. We propose a new approach to easily creating 3D geometric models. A technique called interactive evolutionary computation (IEC) is introduced to accelerate user’s invention and inspiration of new shapes. The proposed IEC-based design system generates aesthetically pleasing shapes through the simulation of natural evolutionary processes. The user is responsible for specifying his/her subjective preference to each shape generated by the IEC. The system allows even beginners with little knowledge and experiences of the 3D modeling to acquire innovative shapes. It also provides skilled experts with an advanced geometric modeling interface based on the implicit surface method. The experts can directly modify the internal parameters of the 3D models to make them more elaborate ones. The result of a preliminary experiment is presented to show the potential of the proposed modeling method.

1. Introduction

As virtual reality (VR) and network communication technologies have dramatically advanced over the last decade, they have been put into practice in many application areas such as product design, manufacturing, education, entertainment, and art. Realistic computer graphics and real-time animation are now accessible technologies for everyone by using standard personal computers and the Internet. There are various software technologies available to share and exploit 3D data on the network such as VRML and Java.

The digital prototyping, as one of the most prospective applications, allows designers to seamlessly design, prototype, and evaluate new products in a networked virtual environment, which significantly increases efficiency and timeliness of the product development. Because the recent development activities give weight to products’ sense and style rather than functions and performance, a design environment to readily sketch the products’ images and 3D shapes stimulating customers’ KANSEI is desired. In spite of these increasing demands for omnifarious and appealing design, the creation of novel and unusual 3D geometries without following conventional modeling techniques still remains a challenging problem to attack.

In this paper, we propose a new digital design framework for easily yielding totally unprecedented 3D shapes. Figure 1 illustrates the concept of our proposed system. We introduce a technique, the so-called interactive evolutionary computation (IEC) [1], as a method for accelerating the designers’ invention and inspiration of new geometric shapes. The proposed IEC-based design system generates fascinating shapes through the simulation of natural evolutionary processes such as crossover, mutation and reproduction according to the designers’ subjective preference. The designers can easily control the IEC-based shape
generation via a simple interface even if they have little knowledge and experiences of the 3D modeling. They only need to subjectively specify the degree of likes or dislikes for the generated shapes by rating, and request the system to discover more preferred models based on the rates. This rating-discovery process is iterated until the system converges on satisfactory results.

We have implemented a 3D modeling system using the implicit surface method in our previous work [2]. It allows the users to intuitively create a complex 3D object by blending a number of primitive shapes. The system, however, expects them to understand its basic functions and acquire some levels of geometric modeling skills, especially preventing beginners from readily making use of it. Therefore, we integrate the IEC interface with the implicit modeling system to realize the framework mentioned above. The implemented system can generally be used for wide range of applications including product design, artwork creation, and even for modeling education for beginners.

![Figure 1: IEC-based 3D modeling concept.](image)

2. Related Work

The IEC is an evolutionary computation (EC) technology that makes the application systems be dependent on human subjective evaluation. The IEC has been applied to several tasks in artistic, engineering, and entertainment fields in these 10 years [1]. One of major application fields is the creative artistic design especially in the initial stage of the IEC research. Dawkins has demonstrated the power of computer simulated evolution to create the boimorphs, the 2D line drawings of complex structures found in the living organism [3][4]. Following his pioneering work, the two representative graphics applications were presented by Sims [5][6][7] and Unemi [8]. They established a concept, the so-called simulated breeding, to generate aesthetic graphics images based on artificial selection rather than natural selection. Although their approach was quite successful to create innovative
results, the target shapes are limited to highly abstract artworks. Other artistic applications are: interactive EC-based drawing lines, such as morphological lines of insects, plant lines based on the L-system, and face drawing: interactive EC-based CG, such as for creating, 3D CG rendering of artificial life art [9], and animal and plants CG [10]: 3D CG lighting design support [11]: industrial designs. See the reference [1] for further detail survey.

A common problem of these applications is their applicability to the experts who have sufficient knowledge, experiences and a clear design objective. They are especially useful solutions for the beginners because all these applications don't assume any detail understandings of graphics theory and the system's internal structures. However, it is difficult for these applications to incorporate the experts fine-grained operations into the IEC process because the only permitted interaction is to evaluate the results generated by the system.

Providing a uniform solution for the users with different skill levels is a difficult problem. Our proposed approach, however, supports from novice to advanced level users by integrating the capability of the IEC-based fresh discoveries with the advanced geometric modeling technology. While the beginners can create their desired shapes by only rating the presented shapes from the system, the experts are permitted to get finer control to generate novel models that are qualitatively better than previous ones. In addition to the IEC-based modeling, the experts can directly modify the internal parameters to make the generated model shapes more elaborate ones.

3. Implicit Modeler Functions

As shown in figure 2, our 3D modeler employs the implicit surface method [12] making easy and rapid creation of rough sketches by smoothly blending primitive shapes possible. The figure illustrates the auto body design examples, including (a) five primitive shapes $P_i$ ($i=1,...,5$) used, (b) a blended shape made of the primitives in (a), (c) a squared body of (b), and (d) a rounded roof of (c). Although the traditional CAD tools can only support the detailed design stages for the experts, our modeler is adequate for the use in the preliminary stages such as 3D sketchy description and conception. It allows the users to easily rough out their ideas and imagination in 3D by iterating the primitive blending and the shape deformation.

A primitive shape is represented by two kinds of superquadric functions [13], that are the superellipsoid to define solid objects and the superspheroid for hollow and cavity shapes as depicted in figure 3(a). Each primitive has eighteen functional parameters as described in table 1. They define its scale, geometric pattern, deformation strength and so on. The shape deformations as those illustrated in figure 3(a) are realized by changing some of these parameter values [14].

Further complex shapes are computed and rendered by blending multiple primitive shapes. Figure 3(b) exemplifies a bottle shape made by blending three primitives $P_1$, $P_2$ and $P_3$. Additional six parameters as described in table 2 control the global deformation and the blending operation. Figure 3(b) indicates the effect of the field strength ($FS$) parameter. Tables 1 and 2 list the actual parameter values to render the bottle shape as illustrated in figure 3(b).
Figure 2: Auto body design examples using implicit surface modeling.

Figure 3: Basic modeling operations.

Table 1: Primitive parameter values of the bottle in figure 3(b).

<table>
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<tr>
<th>type</th>
<th>r₁</th>
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<th>r₃</th>
<th>r₄</th>
<th>c₁</th>
<th>c₂</th>
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<th>d₁₂</th>
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<td>0</td>
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Table 2: Blending parameter values of the bottle.

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<th>D₁₂</th>
<th>D₁₂</th>
<th>D₁₂</th>
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<tbody>
<tr>
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<td>1.4</td>
<td>0.15</td>
<td>0.15</td>
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</table>

4. IEC-based 3D Modeling

The implicit modeler as mentioned in the previous section still demands the users understanding of which parameter needs to be modified to perform a desired deformation. Additionally, generic understanding of the geometric modeling also helps them to produce the preferred 3D models effectively. These requirements significantly prevent the beginners from concentrating on the design tasks, enforcing them to become familiar with the operations provided by the modeler. Our solution to this problem is to support a simple yet powerful modeling option by incorporating the IEC technology, allowing even beginners to intuitively explore aesthetically pleasing forms and shapes.

The proposed IEC-based 3D modeling uses two separate spaces: the search space and the solution space as shown in figure 4 [15]. We adopt genetic algorithms (GAs) as one of the EC technologies in this paper. While the search space is a space of coded solutions to the problem (3D model generation), the solution space contains actual solutions (3D models). A coded solution, or GTYPE (genotype), must be mapped onto an actual solution,
or PTYPE (phenotype). A PTYPE consists of a set of the parameter values representing a specific 3D model. Figure 4 illustrates the PTYPE and the GTYPE of the bottle shape mentioned in the previous section. The PTYPE consists of three primitive (P₁, P₂ and P₃) and one blending (B) parameters, and the corresponding GTYPE composes a bit string of all parameters held in the PTYPE. Each parameter is encoded as an 8-bit string, the so-called gene, and a collection of genes in one GTYPE is referred as a chromosome. The bit length of the chromosome is given as \( p \times n + b \), where \( p \) is the number of primitive parameters; \( n \) is the number of primitives; \( b \) is the number of blending parameters. Therefore, the length of the chromosome of the bottle shape in figure 4 is 60 bytes (18x3+6).

Figure 4: IEC-based 3D modeling mechanism.

IEC maintains a population of individuals where each individual consists of a PTYPE and its corresponding GTYPE. Figure 5 summarises the IEC-based modeling algorithm. First of all, an initial set of GTYPES is randomly created and then decoded to PTYPES for rendering.
3D models. Next, a user rates the fitness value for each rendered model according to his/her subjective preference as written in boldface in figure 5. Then, a new set of GTYPEs (offsprings) is generated from existing GTYPEs (parents) by using crossover and mutation as shown in figure 4. The crossover operator creates offsprings by exchanging genes of two parents. While crossover operation is frequently executed, mutation is occasionally applied to a chromosome with a low probability; e.g. 80% crossover rate and 1% mutation rate are used in our preliminary experiment as described in section 6. High scored GTYPEs have high probability to survive, being selected as parents to generate new offsprings. This generation and evaluation process is iterated until acceptable model shapes are produced.

```plaintext
randomly generate an initial set of GTYPEs;
do {
    decode GTYPEs to PTYPEs for rendering 3D models;
    rate fitness value for each PTYPE by user;
generate a new set of GTYPEs by using evolutionary operations;
} while (there is no acceptable solution)
```

Figure 5: IEC algorithm for 3D model generation.

Although ordinary genetic algorithms (GAs) utilize an explicit evaluation function to automatically measure the fitness of the PTYPE, they don’t permit the users to be involved in the evolutionary design. Whereas the IEC depends on the human opinions to judge the aesthetic quality of the generated models, it enables the users to loosely control and direct the results even if they have no sufficient knowledge and experiences for the 3D modeling task.

5. System Interface

As mentioned in the previous sections, the IEC-based modeling depends on the users direction and evaluation to get successful results from the simulated evolution. Therefore, the interface to allow the users to easily find their preferred shapes and properly set the fitness values is a crucial element to realize. Additionally, a mechanism for providing the experts with finer control on the modeling process is a very important requirement in our framework design. Consequently, we implemented the interface consisting of two different windows as shown in figure 6. The 3D models generated through the IEC process are simultaneously displayed in a list format as depicted in figure 6(b). The users can look at upto twenty generated models at the same time, comparing one another, and assessing whether the shape is good or bad. The main window as shown in figure 6(a) is provided for the use by the experts who have sufficient modeling skills. The experts are allowed to invoke a specific shape in the IEC display to the main window, performing the exquisite deformations by setting the definite model parameters. This bidirectionally accessible interface between the two windows enables the experts to synergistically utilize the both functions, namely the IEC-based innovative shape discovery and the implicit modeling for the elaborative design. The users set the fitness values and the model parameters via the slider GUI elements as illustrated in figure 6(c). The slider can be handled only by a mouse device to make the users be concentrating on the modeling tasks. The actual operation is to select the slider icon by the mouse and move it with holding the button as described in figure 6(c). The values are modified in proportion to the mouse movements.

Although the better operational environment should simultaneously make both windows visible on a wide screen or dual monitors, they can be swapped back-and-forth on a single small monitor system. Figure 7 shows our operational environment implemented by using an SGI Onyx2 graphics computer with a large arch screen as a display device. Because the wide
screen projection system provides superior operational environment, it is a promising technology to become a common output device in the near future.

Figure 6: IEC-based 3D modeling interface.

Figure 7: Operational environment with large arch screen.

6. Preliminary Experiments

6.1 Experiment for Beginners
We conducted a preliminary experiment to test the effectiveness of the proposed system for creative 3D modeling. To verify the system’s ability to support the beginners, a green pepper is used as the target shape in the experiment because of the following reasons:

1. Everyone easily imagines its shape without depending on his/her knowledge and experience,
2. It is an inartificial shape which is difficult to design by using the traditional CAD tools, and
3. Its shape has enough variations to encourage the subjects’ flexible thinking and imagination.

Figure 8 shows a result of the experiment performed under the following conditions:

- The population of individuals is 20,
- The crossover rate is 80%,
- The mutation rate is 1%, and
- The fitness value is a rate on a scale of 1 to 5 (the worst to the best correspond to 1 to 5).

While 16 offsprings (80%) out of 20 are generated by the crossover operation in every generation, the remaining 4 slots (20%) are reserved for the highly scored elite parents to survive.

As easily perceived from figure 8, a few initial generations seem to include randomly generated shapes. There are, however, several shapes looking like the green pepper in the 3rd to the 5th generations. Then the continuous allocation of highest scores to these likely shapes makes the 7th be close to a point of convergence. Finally, nearly all shapes in the 10th generation look like the target.

We employed a few beginners as subjects for this experiment, and all of them completed the modeling within about 30 to 60 minutes. The observed variation in the modeling time depends on the operational performance for setting the fitness value and does not associate with the number of generations reproduced. All subjects finally get the target shape in the 8th to 10th generation. To further improve its operationality, the mouse device can be replaced by some other intuitive spatial interaction methods such as voice and gesture [16].

Enormous amount of training time and efforts is required for the beginners to create the shape like the green pepper by using the traditional CAD tools. Therefore, the proposed IEC-based modeling is thought to be a quite useful method to support creative modeling for the beginners.

6.2 Experiment for Expert Users

The beginners-oriented modeling method as explained in 6.1 is not always a suitable approach to the expert users who can skilfully handle the 3D modeler. Because they tend to have existing 3D models designed for their own goals and targets, it seems to be desirable to start the new shape creation from such existing models rather than from scratch. Therefore, we add an optional function to load the pre-existing 3D models as the initial set of GTYPES in stead of the randomly created ones in the IEC algorithm as mentioned in figure 5.

Figure 9(a) shows some variations of hollow bottle models derived from a single initial shape and figure 9(b) presents the example solid models spawned from the four initial shapes. The experimental conditions such as the population of individuals, the crossover rate, the mutation rate, and the fitness value rate are the same with the test as described in 6.1. All these models are created in a few generations up to the 5th.

Although the system yields interesting variations even by using a single shape, the result proves that the more initial shapes are specified, the more novel and surprising forms appear. Eliminating artificial and geometrical properties of the models to make them look real and natural is very difficult issue for everyone in the 3D modeling. Figure 9 reveals a
fact that the proposed method is effective for the experts to offer stimulative new ideas by suggesting inartificial and unexpected shapes.

Figure 8: Experimental result to make green pepper.

7. Conclusions and Future Work

We proposed a new 3D modeling system based on the IEC technology. The system allows the users to generate entirely new shapes starting from little or nothing through the interaction with the simulated evolution. The system’s potential for creative design has been shown by our preliminary experiments.

Conducting more comprehensive modeling experiments by different target shapes and subjects with various skill levels is the second stage of our research. Because the system efficiency highly depends on the users’ performance to perceptually select and evaluate their preferred models, the subjective tests and their statistical analysis also are very important studies. Further enhancements such as the integration of the VR interaction
methods [16] and the incorporation of the distributed data sharing capabilities [17] are planned to make the system be usable for various application domains on the network.

Figure 9: Experimental result to create new models from pre-existing shapes.

References