Special Issue: CAD in the Arts

Guest Editor: Carlo H. Séquin, University of California, Berkeley

An Aesthetics Driven Approach to Jewelry Design

Somlak Wannarumon, Naresuan University, somlakw@nu.ac.th

ABSTRACT

This paper proposes a computer-based design tool to automate art form generation used in jewelry design. Expert system and evolutionary algorithm are integrated into the prototype design tool named *JAFG* (Jewelry Art Form Generator). Art forms are represented using iterated function system (IFS) fractals. Case-based reasoning method and fuzzy logic are used for calculating case similarity to increase the efficiency of existing art forms retrieval. An evolutionary algorithm is used as a mechanism to generate new art forms. A rule-based reasoning with a forward chaining IF-THEN rule method is applied to estimate production cost. An automated model-making module integrated into the design system provides users with an option to manufacture jewelry prototypes using a computer numerical control (CNC) or a rapid prototyping (RP) machine. Examples are given to illustrate how *JAFG* operates.

Keywords:computer design support, evolutionary art, fractal, jewelry design.
DOI: 10.3722/cadaps.2010.489-503

1 INTRODUCTION

Conceptual design is an early stage of a generic design process. It usually has the characteristics of fuzzy problems with a high degree of uncertainty. During conceptual design, designers typically create lots of ideas and turn them into quick sketches with pencil and paper. Computer-aided design (CAD) software is rarely used in the conceptual design stage, because it usually requires complete, concrete, and precise definitions of design geometries, which are available only in the subsequent detailed design stage.

Computer-aided art and design tools play a key role not only in conceptual design but also in the entire development process, helping artists and designers from the initial conceptual ideas, through the optimization of the design parameters. Several examples were developed by Carlo H. Séquin including *Sculpture Generator I* , which is a computer program for the design and visualization of Scherk-Collins hole-and-saddle chains warped into toroidal configurations, that can demonstrate the roles of computer-aided design tools in the creation of geometrical shapes, shape optimization and aesthetic considerations [14-16].

Artificial intelligence (AI) plays an increasingly important role in design applications for shape optimization and integration of design information. AI such as expert systems (ES) employs human

© 2010 CAD Solutions, LLC

knowledge to solve problems that normally would require human intelligence and design reasoning. Evolutionary algorithm (EA) can help designers in design optimization and breeding new designs based on existing forms. Two computer-based jewelry design systems were previously developed by the author. One was developed based on an expert system [22] and the other was developed based on an evolutionary algorithm [21,23].

In this paper, ES and EA are integrated into a single design system named '*JAFG*' (Jewelry Art Form Generator) to improve the efficiency of the previously developed computer-aided design tools.

The process begins with the designer selecting the relative importance of various design characteristics. The system then retrieves a set of designs that most closely match the presence of the desired attributes from a database of previous designs. The system uses these designs as the parents in a genetics-based evolutionary algorithm to produce related design off-springs. From these the user selects other appealing specimens as parents for further evolution of the design.

Case-Based Reasoning (CBR) with a fuzzy similarity measure is applied to improve the efficiency of the retrieval process of previous designs[21,23]. The main objectivesare to provide more variety in the designs and to reduce the overall processing time of the system.

Rough production costsare also derived and stored in the cost estimating module of the system. This helpsthe designer to estimate the production cost of an evolving design.

The prototype system is currently limited to the design of jewelry rings without gem setting.

2 LITERATURE REVIEW

2.1 Expert System

A design system for jewelry based on ES and CBR has previously been reported [22]. That system was limited in the size of its jewelry design database and the variety of jewelry it could generate. Kowalski et al. presented a CBR methodology for similarity calculations, which was applied in an ES to aid the automated design of engine rooms in ships[10]. CBR was used for finding ship designs in the database of previous designs, similar to the design being created. The system makes designing the monitoring and automation systems for a ship's engine room much easier and simpler.

An intelligent knowledge-based system was developed for modeling the product costs of machining components [17]. Hybrid knowledge representation techniques such as production rules, frames, and an object–oriented approach, were applied to represent manufacturing knowledge concerning machining components. Fuzzy-logic-based knowledge representation was applied to deal with the uncertainty in the knowledge of the cost model. The system could be applied without having detailed design information; therefore it can be used at the conceptual design stage.

The case-based reasoning method finds solutions from a case database by matching the new problem situation to past cases, retrieving the most similar case and adapting it to the current problem [11]. A case-based system consists of two main parts, a case database and a problem solver. The case database contains the description of the problem, the solution to the problem and the outcome. Each case is assigned an index for retrievalpurposes. The problem solver works by searching through this database and retrieving a case that is most similar to the current problem. The similarity to the current case is calculated by comparing each individual characteristic of the new case with all the previous cases in the database.

In a rule-based reasoning method, the knowledge base contains domain-specific knowledge in the form of IF-THEN rules, and its working memory contains problem-specific facts and conclusions derived by an inference engine [5]. A rule-based system typically has two operation modes: backward and forward chaining. In backward chaining, the system is given a set of goals, and it then attempts to prove this goal by using the rules along with information provided by users. Forward chaining has no specific goal to prove. It attempts to derive information from the available problem-specific facts by firing many rules until no further rule can fire given the information in the working memory.

© 2010 CAD Solutions, LLC

2.2 Evolutionary Algorithm

Evolutionary art and design systems provide an effective way to create attractive pieces of art, which possess very distinct styles but are mostly non-functional. In an evolutionary art system, the evolutionary process works as a form generator that provides a wide variety of forms, rather than as a form optimizer. As a consequence, designers typically explore more design alternatives. Most of the evolutionary art and design systems generate new forms based on some random initial population. Each individual of that population may be evaluated for its fitness by a human artist or by a computer. The user interface is usually designed to help a designer to easily evaluate the fitness of any individual and to rank or select different individuals. The evolutionary process then generates new art forms based on the individuals with the highest fitness ranking. This process employs the advantages of evolutionary form growing for improved shape generation.

The following are the major elements of an EA [3]:

Genotype is a genetic code representation that contains all information for generating a specific individual. Genotypes are typically encoded in the string of chromosomes, which can be used as the basic units of evolutionary changes. The suitable structures and representations of genotypes allow us to easily apply genetic operators. Genotype can be encoded in both binary and real numbers. Before the quality (fitness) of each solution is evaluated, the genotypes are mapped onto the actual solution (phenotypes). The phenotypes generally consist of sets of parameters representing shapes or forms. Art forms (phenotypes) have been represented by several techniques depending on the systems' purposes.

New versions of off-springscan be produced by genetic crossover or mutation operators. Crossover is an event where parts of the chromosomes of the two selected parents are exchanged. The resulting off-springs then inherit the characteristics of both parents. Mutation changes an arbitrary part in a genetic sequence from its original state. Mutation is used to maintain population diversity during evolution.

Fitness function represents a heuristic estimation of the solution quality. It is derived from the objective functions, to measure the phenotypes' abilities or properties. For every phenotype its fitness or some other measure of goodness must be evaluated. In an EA system, almost all computational time is spent in the evaluation process [3], which can take several minutes to many hours to evaluate a single solution. The process can be accelerated by reducing the number of evaluations performed in each generation. Population size may be kept to less than ten individuals [3], which can then be judged rapidly in each generation. Selection is the process of choosing suitable phenotypes according to their fitness. It plays a key roleincontrolling the evolutionary process.

There have been many publications demonstrating the use of ES systems in design applications, including the creation of artistic forms, e.g.,[2],[3],[4],[6],[9],[12],[13],[18],[19],[24].

A new evolutionary design approach is presented here for the creation of non-functional art forms for jewelry design [21,23]. These art forms are modeled using fractal geometry generated by iterated function system (IFS) [1]. The interactive evolutionary design system is specifically aimed at novice userssince it employs a user-centered design approach.It alsoprovides an enhancement of the resulting algorithmic aesthetics.

2.3 Fractal Geometry and Iterated Function System (IFS)

An IFS fractal is made up of the union of several copies of itself, each copy being transformed recursively by an affine transformation (scaling, rotation, shearing and translation) [1] (pp. 80-81). The IFS is an easy way for generating fractals with self-similar aesthetic patterns with minimal time and space complexity.

The IFS consists of a complete metric space (X,d) together with a set of the contraction mappings with contraction factors s_n, $|s_n| \leq 1$ for $n = 1,\ 2,\ \dots\ N$, where n is an index for each affine map. Affine transformation of a point set in the Euclidean plane is defined as a map $w:\mathbb{R}^2 \to \mathrm{E}^2$ and $w(x,y) = (ax + by + e, cx + dy + f)$, where real numbers $a,b,c,d \in [-1,1]$ and $e,f \in (-\infty,\infty)$.

An IFS consists of a finite number of contraction maps;it can be rewritten in matrix form as

$$w(x,y)=\begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}+\begin{pmatrix} e \\ f \end{pmatrix} \tag{2.1}$$

Any IFS consists of at least two affine transformations. Each transformation has its own selection probability p_i. This probability determines the frequency with which an affine transformation will be selected from the IFS to be applied to the point set in random iterations (RIA) [1] (pp. 87-90).

For rendering the fractals resulting from an IFS, Barnsley introduced the approximation of selection probability p_i of each affine transformation A_i [1] by:

$$p_i \approx \frac{\left|\det A_i\right|}{\sum_{i=1}^{N}\left|A_i\right|}=\frac{\left|a_i d_i - b_i c_i\right|}{\sum_{i=1}^{N}\left|a_i d_i - b_i c_i\right|} \tag{2.2}$$

where $\sum_{i=1}^{N} p_i = 1$ and $p_i > 0$. This equation is based on fast convergence for rendering the corresponding fractal.

Referring to Elton's theorem [1] (pp. 364-378), we can explain the process of RIA in the following way. Given an initial point $x_0 \in \mathbb{R}^2$. One of the affine transformations from the set $\{w_1, w_2, ..., w_N\}$ is selected at random by the probability p_i for $i = 1,2,...,N$. The selected transformation is then applied to x_0 to produce a new point $x_1 \in \mathbb{R}^2$. The process is repeated in the same manner to produce the successive new points until the predetermined number of iterations (a positive integer) is reached.

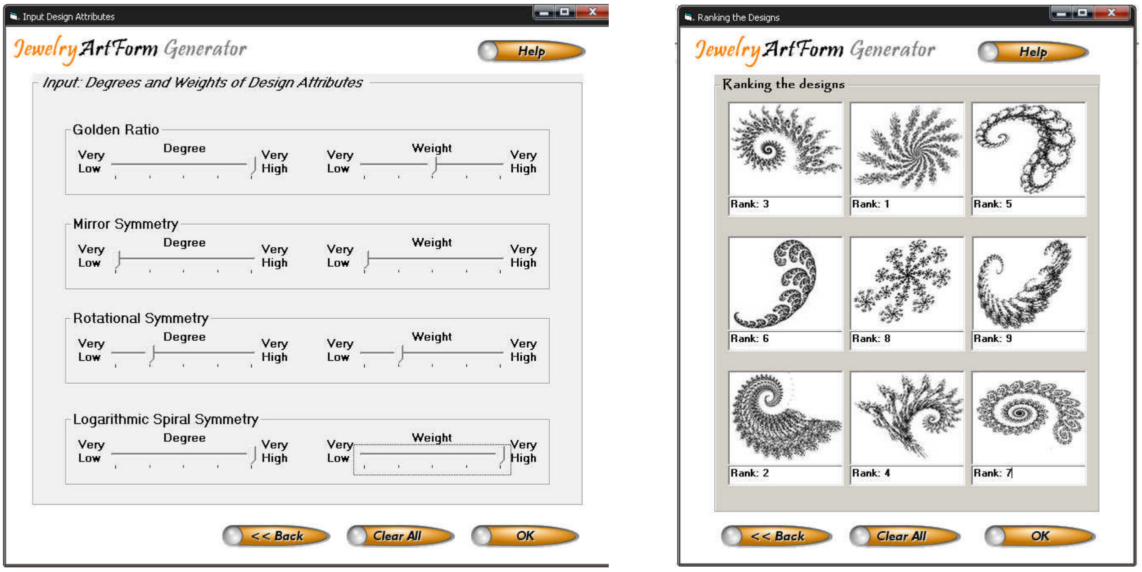
3 FRAMEWORK OF AN INTELLIGENT AESTHETICS DRIVEN JEWELRY ART FORM GENERATOR

The techniques of expert systems and of evolutionary algorithms are applied in our*JAFG* system for automatically generating jewelry art forms. It consists of three modules. The first module is the '*Designer Interface*', which makes it easy for a user to input initial shape specifications and then to collaborate with the system in the evolution of a design. The second layer, labeled 'Algorithmic Design', contains: the '*Form-Generating Algorithm,*' which retrieves similar shapes from the design database; the '*Form-Evaluating Algorithm,*' which quantifiesa form's morphology and aesthetics; and the '*Cost-Estimating Algorithm,*' which uses rule-based reasoning to estimate the production cost of thecurrent design. The third layer contains the '*Automatic Model Making Module,*' which links the design system to a computer numerical controlled (CNC) machine or to a rapid prototyping (RP) machine for quickly fabricating physical models of the design. These physical models can then be used as master models in a lost-wax casting process to create actual jewelry pieces.

3.1 Designer Interface

There are several tasks for a designer in interacting with this system: defining the design attributes and their respective weights; evaluating the generated designs during the evolutionary process; terminating the process when the result is satisfactory; and forwardingmanufacturing information.

As a start, the designer selects thedesirability of various design attributes (golden ratio, mirror symmetry, rotational symmetry, and/or logarithmic spiral symmetry). The details of these attributes are explained in the subsequent sections. The desirability of each design attribute and its respective weight are defined in terms of five language expressions: very low; low; medium; high; and very high. Both parameters can be input to the system through the scroll bars on the user interface shown on the left screen in Figure 1.



Rank: 3
Rank: 1
Rank: 5
Rank: 6
Rank: 8
Rank: 9
Rank: 2
Rank: 4
Rank: 7

Fig. 1: Some screens of the user interface of *JAFG*.

The *degree* of a design attributes specifies how much the design should contain the particular design attributes. For example, if the designer defines the degree of a design attribute, e.g.*golden ratio,*to bevery high, it indicatesthat she prefers to obtain adesign which there are many objects fully respecting the golden ratio. The defined *weights* signify how much relative importance the designer gives to a particulardesign attribute. For example, if the design assigns the weight of the golden ratio to bemedium, this attribute will be given a weight equal to the average weights of the other attributes when there are conflicting priorities.

During the evolutionary phase of the design process the user needs to make selections repeatedly. For this purpose the system displays a screen with multiple phenotypes,as shown in the right panel of Figure 1. The user then evaluates the displayed designs by entering numerical rankings (from 1 to 9) for each design. After each iteration round, the user can choose to terminate the process (by clicking on the preferred design) or to continue with further iterations (by clicking the OK button). The process can also be terminated automatically after a predefined number of generations.

If the designer wants to produce a physical artifact, some manufacturing information has to be specified, such as the types of material to be used, the type of prototyping, the casting process, and the type of finishing,as well as the number of pieces to be produced. This information is input to the system through a set of ‘dropdown menus.’It will also be used for rough cost estimation, discussed in Section 3.2.3.

3.2 Algorithmic Design

The algorithmic design system consists of a knowledge base and of three main modules: the case-based reasoning module,the evolutionary algorithm module, and the rule-based reasoning module. The knowledge base consists of three main databases: a repository for the previous design cases,a listing of different materials,and a set of known production processes.

The system first retrieves some existing art forms from the design case database by using case-based reasoning method with a fuzzy similarity measure. The retrieved art forms are used as the initial populations in the EA system developed by Wannarumon et al. [23].

3.2.1 Case-Based Reasoning Module: Fuzzy Logic Similarity Calculation

This part describes a new module that was not contained in the previous design tool [21-23]. The case-based reasoning module is used for retrieving a set of existing designs from the database. This module has two main components: the design case database and the problem solver, which deals with case retrieval and reasoning.

Each new design receives its fuzzified encoding when it is first added to the database. The match for each of the four attributes is based on the overlap of their respective triangular fuzzy-logic membership functions shown in Figure 2.

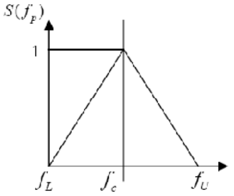


Fig. 2: Triangular similarity function.

The triangular function is given by:

$$S(f_p)=\left\{\begin{array}{l} \dfrac{f_p-f_L}{f_c-f_L}\ ,\quad f_L\le f_p<f_c \\ \dfrac{f_U-f_p}{f_U-f_c}\ ,\quad f_c\le f_p<f_U \\ 0\ ,\quad f_p<f_L\ and\ f_p>f_U \\ \end{array}\right\} \tag{3.1}$$

where $S(f_p)$ is the similarity value of a previous case to the new case; f_p is the parameter value of the previous case; f_c is the parameter value of the new case; f_L is the lower limit value of f_c; and f_U is the upper limit value of f_c.

The shape that is most similar to the designed one is found based on the maximum fuzzy similarity result. This shape is then used as a parent in the evolutionary algorithm module.

3.2.2 Evolutionary Algorithm Module: Art-Form Generation and Evaluation

The IFSs are encoded in variable-length chromosomes to represent an art-form genotype. The IFS compact sets are encoded in the basic unit of evolution, the gene. The genes are composed into a chromosome expressing itself as a genotype (or an individual) to represent an art form. A chromosome consists of at least two genes (or affine maps) shown in Figure 3.

Each gene consists of six alleles $\{a,\ b,\ c,\ d,\ e,\ f\}$ of an affine transformation, where $a,b,c,d\in[-1,1]$ and $e,f\in[-50,50]$ are real numbers. The alleles a and d control 'scaling' in x and y axes respectively. The alleles b and c control 'shearing' in x and y axes respectively. The alleles e and f control 'translation' in x and y axes respectively.

A rotation is being carried out using matrices. The point (x,y) to be rotated is written as a vector, and then multiplied by a matrix calculated from the angle θ:

$$\begin{pmatrix} x' \\ y' \end{pmatrix}=\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} \tag{3.2}$$

andtheIFS can then be rewritten in the form:

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix}=\begin{pmatrix} r_1\cos\theta_1 & -r_2\sin\theta_2 \\ r_1\sin\theta_1 & r_2\cos\theta_2 \end{pmatrix} \tag{3.3}$$

where (r_1,θ_1) is the polar coordinate of the point (a,c) and $(r_2,(\theta_2+\pi/2))$ is the polar coordinate of the point (b,d).

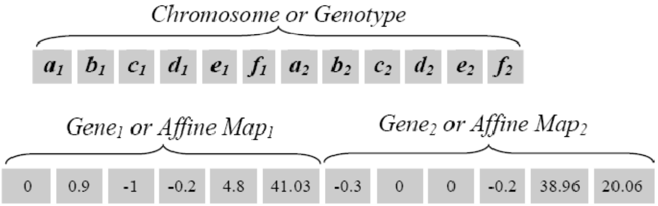


Fig. 3: An example of chromosome encoding.

The IFS chromosomes are stored in the design database. The resulting point-cloud fractals will be generated by decoding the IFS using RIA [1] (pp. 87-90). The genetic operators, multi-Gaussian mutation and modified arithmetic crossover [21,23], are developed for producing a new set of design alternatives with high diversity, while simultaneously maintaining good forms.

In the multi-Gaussian mutation, a set of Gaussian random numbers are applied to all of the alleles simultaneously within the defined mutation rate (5%). The modified arithmetic crossover covers single- and multiple-point crossover. The crossover points are randomly selected by the system, butarealways located in such a way that individuals exchange complete sets of affine transformation parameters,as shown in Figure 4.

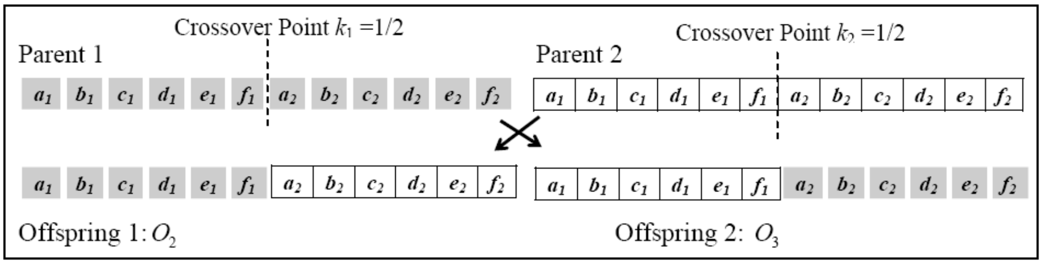


Fig. 4: An example of the operation of modified arithmetic crossover.

The following four design attributes are used for retrieving and evaluating the aesthetics of the generated art forms.

3.2.2.1 Golden Ratio

Golden ratio expresses the appropriate ratio of two sub-parts. If a line is divided into two sub-parts, the ratio of smaller sub-part to the larger sub-part is the same as the ratio of the larger part to the whole line. The golden ratio is often associated with aesthetic appeal in arts and architectures [8]. Golden ratio is usedto construct a 'golden rectangle,' which is then used a pleasing shape for many artifacts [8] (pp.53). A square ABCD is constructed (Fig. 5), and then the side AB of the square is bisected in E. Using E as a center with the radius EC, we then draw an arc of a circle cutting AB produced in G. Then AFGD is a golden rectangle and it has sides with a ratio $1:\phi$ shown in Figure 5.

© 2010 CAD Solutions, LLC

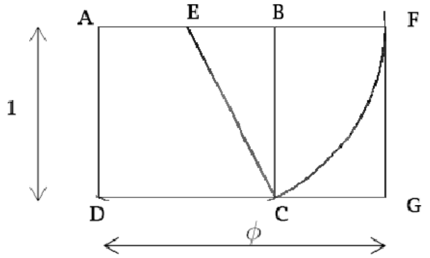


Fig. 5: Construction of a golden rectangle [8] (pp.61) with minor additions.

To quantify the golden ratio in a particular design, our algorithmstarts by defining two perpendicular directions. The reference axis A is perpendicular the *finger*, while the reference axis B is along the finger shown in Figure 6.

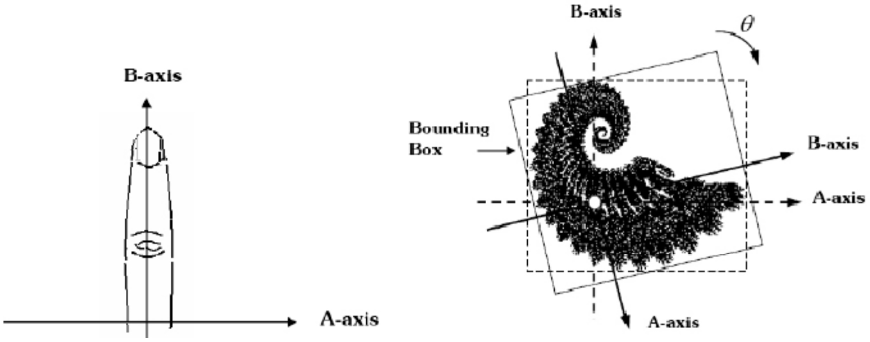


Fig. 6: The reference axes related to human finger (left) and their overlay on an IFS fractal (right).

This coordinate system is then placed at the centroid of the fractal, and the width (*W*) and the length (*L*) of the bounding box are computed. The deviation from the golden ratio ϕ is calculated as

$$\Delta = \left|(W / L) - \phi\right| \tag{3.4}$$

where the reference golden ratio ϕ=1.6180339 [8]. We thenevaluate thisdifference in the normalized range of [0, 1]

$$G = e^{-\Delta} \tag{3.5}$$

The reference axes are now rotated until the maximum value of G is obtained. This maximal value of $G$is used as an indicatorhow close that part of the design comes to satisfying the desire to exhibit the golden ratio.

3.2.2.2 Mirror Symmetry

Like the golden ratio, the mirror symmetry depends on the same reference axes. We find the centroid of the fractal, and then place the reference axes on it. Using the morphological image processing techniques described in[7], the fractal is splitinto two parts bythe *B*-axis, and then the difference between the left part L_{part} and the right part R_{part} is computed as

$$\Delta M = \left|L_{part} - R_{part}\right| \tag{3.6}$$

Again we rotatethe reference axes until aminimum value of ΔM is obtained. ΔM lies within the interval [0, 1].

3.2.2.3 *Rotational Symmetry*

The rotational symmetry of IFS fractal can be measured from the properties of similitude [1] (pp. 54-64). To measure the similitude of each affine transformation, IFS is rewritten in the polar form shown in Eqn. (3.3). Any IFS that has rotational symmetry contains at least one rotational affine map. The followings are the condition for measuring the rotation of affine map:

1. $\Delta(\theta_1,\theta_2)$, $\theta_1-\theta_2\to 0$ and $\Delta(r_1,r_2)$, $r_1-r_2\to 0$,
2. $\theta_1,\theta_2\geq 45^\circ$ and $r_1,r_2\to 1$.

Then $\Delta(\theta_1,\theta_2)$ is divided by 90° for normalizing it to [0, 1]. The rotation factor is defined as: $\theta_R=1-(\Delta(\theta_1,\theta_2)/90^\circ)$, where θ_R is a rotation factor, then $0\leq\theta_R\leq 1$, and $0\leq\Delta(r_1,r_2)\leq 1$, $r_R=1-\Delta(r_1,r_2)$, where r_R is a scaling factor.

Thus, the rotational symmetry is formulated as

$$R^T=(\theta_R+\theta_{1\mathrm{R}}+\theta_{2\mathrm{R}}+r_R+|r_1|+|r_2|)/6 \tag{3.7}$$

where R^T = rotational symmetry value, $0\leq R^T\leq 1$,

$$\theta_{1\mathrm{R}}=\begin{cases}1, & \text{if } \theta_1\geq 45^\circ,\\ 45^\circ-\theta_1, & \text{if } \theta_1<45^\circ.\end{cases}\quad ,\ 0\leq\theta_{1R}\leq 1,$$

$$\theta_{2\mathrm{R}}=\begin{cases}1, & \text{if } \theta_2\geq 45^\circ,\\ 45^\circ-\theta_2, & \text{if } \theta_2<45^\circ.\end{cases}\quad ,0\leq\theta_{2R}\leq 1,$$

r_R = scaling factor, $0\leq r_R\leq 1$.

3.2.2.4 *Logarithmic Spiral Symmetry*

Like the rotational symmetry, the logarithmic spiral symmetry can be quantified by measuring the similitude of affine transformation with the following conditions:

1. $\Delta(\theta_1,\theta_2)$, $\theta_1-\theta_2\to 0$ and $\Delta(r_1,r_2)$, $r_1-r_2\to 0$,
2. $\theta_1,\theta_2<45^\circ$ and $r_1,r_2\to 1$.

The logarithmic spiral symmetry will appear when the rotation angles of affine map are over than 45°. The logarithmic spiral symmetry is derived in the same manner of the rotational symmetry:

$$L^T=(\theta_R+\theta_{1\mathrm{R}}+\theta_{2\mathrm{R}}+r_R+|r_1|+|r_2|)/6 \tag{3.8}$$

where L^T = logarithmic spiral symmetry value, $0\leq L^T\leq 1$,

$$\theta_{1\mathrm{R}}=\begin{cases}1, & \text{if } \theta_1<45^\circ,\\ \theta_1-45^\circ, & \text{if } \theta_1\geq 45^\circ.\end{cases}\quad ,\ 0\leq\theta_{1R}\leq 1,$$

$$\theta_{2\mathrm{R}}=\begin{cases}1, & \text{if } \theta_2<45^\circ,\\ \theta_2-45^\circ, & \text{if } \theta_2\geq 45^\circ.\end{cases}\quad ,0\leq\theta_{2R}\leq 1.$$

3.2.3 *Rule-Based Reasoning Module: Cost Estimation*

This module contains IF-THEN rules with forward chaining of material selection and production techniques to estimate material costs, labor costs, machine costs, and processing costs. In this study, the rough production cost of a jewelry product is computed from the processing costs and the material costs:

$$C_T = C_P + C_M \tag{3.9}$$

where C_T is the total production costs (\$); C_P is the process costs (\$); and C_M is the material costs (\$).

The processing costs of a jewelry product consists of the costs of several production processes such as prototyping, mold-making, casting, and finishing:

$$C_P = \sum_{i=1}^{N} \frac{PC_i \bullet PT_i}{NP_i} \tag{3.10}$$

where PC_i is the process cost rate (\$/hour/batch) of the machine i for i= 1, 2, 3, ..., N (N is the number of machines); PT_i is the processing time (hour/batch); and NP_i is the number of workpieces in a batch (pieces/batch).

The process cost rate is comprised of machine cost rate and labor cost rate:

$$PC_i = MC_i + LC_i \tag{3.11}$$

where MC_i is the machine cost rate (\$/hour/batch) and LC_i is the labor cost rate (\$/hour/batch).

The machine cost rate of the machine i is calculated from:

$$MC_i = (1 + O_i)\left(\frac{MP_i}{AP_i \bullet WY}\right) \tag{3.12}$$

where O_i is the overhead (%); MP_i is the machine cost (\$); AP_i is the amortization period (years) and WY is the working hours per year (hours).

The material cost is calculated from the material unit price and the weight of the workpiece:

$$C_M = \sum_{j=1}^{M} MU_j \bullet W_j \tag{3.13}$$

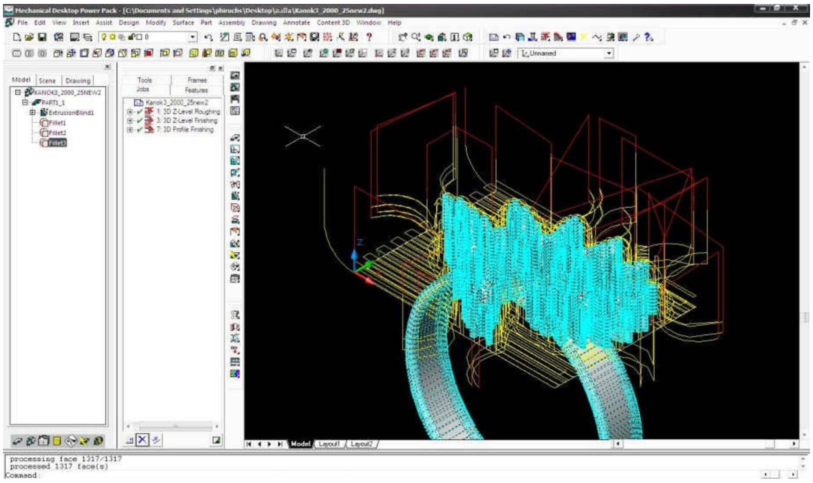
where MU_j is the material unit price (\$ $/g$) of the material j for j = 1, 2, 3, ..., M (M is the number of machines) ; and W_j is the weight (g) of material of the proposed design.

3.3 Automated Model-Making Module

The art form that is generated by our system is in a form of point cloud. In this study, the point cloud is shown as the ornamental part of a jewelry ring. The two point clouds of the ornament part and of the ring shank are transformed to a combined three-dimensional (3D) surface model using Geomagic Studio software. The combined point cloud is imported into Geomagic Studio and by using the 'Wrap' option in the 'Point' function, a boundary representation surface model of the decorated ring is then created.

The model-making module inside*JAFG* provides two options for automatically fabricating jewelry prototypes. The first is based on computer numerical control (CNC) machining. A CAD module from AutoCAD and a CAM (computer-aided manufacturing) module from Mechanical Desktop with hyperMILL are integrated into *JAFG* for simulating the milling of a prototype on a CNC machine.*JAFG*calculates the necessary tool paths and NC codes. Examples of the machine paths for two different milling tools are shown in Figure7. The first tool with a diameter of 2 mm is for roughing, while the second one with a diameter of 1.5 mm is for finishing. The blue lines represent the surface area of the target object calculated by hyperMILL. The yellow lines represent the tool paths for the roughing and surface finishing milling operations. The red lines show the tool movements between active milling operations.

The second manufacturing method supported by *JAFG is* rapid prototyping (RP) based on layered manufacturing [20]. For this purpose the boundary representation of the finished design is output in the stereolithography (STL) format. A preliminary file description is created by the AutoCAD module; this representation is then verified and fixed by using Magics software.



```
processing face 1317/1317
processed 1317 face(s)
Command:
```

Fig. 7: An example of the machine paths for two milling tools.

4 RESULTS AND DISCUSSIONS

The prototype design system was developed using MATLAB V.7.0 on a computer with CentrinoCore™ 2 Duo CPU Processor 1.8 GHz and 1.99 GB of RAM.

4.1 Experimental Results

A design case database with three-hundred various designs was constructed in *JAFG*. Fifty of these designs were generated manually, while the rest were automatically generated by using the previous system [23]. The working process of *JAFG* and its results are illustrated in the following experiments.

Before the first time use of *JAGF*, it is necessary to provide a novice user with user instructions explaining the system concept, the system flow and the characteristics of the design attributes (golden ratio, mirror symmetry, rotational symmetry and logarithmic spiral symmetry) and what they look like.

In one example experiment, a user defined the design attributes as presented in Table 1.

Design attributes	*Degree*	*Weight*
Golden ratio	High	High
Mirror symmetry	Very low	Low
Rotational symmetry	Low	Medium
Logarithmic spiral symmetry	Very high	Very high

Tab. 1: An example of the degrees and weights of the design attributes defined by a user.

A set of twenty previous art forms was retrieved from the database based on these attributes; this took a total of 16 seconds for searching and decoding in the database. These best matches were displayed on the screen,where the user chose two of them for mating, shown in Figures8(a) and 8(b).

The two art forms selected by the user were used as the parents in the first step of the evolutionary algorithm. Breeding while using the crossover operation produced the two off-springsshown in Figures8(c) and 8(d). These designs were individually modified by using the mutation operation multiple times as shown in Figures8(e) and 8(f). The computation time of this phase of the experiment was 119 seconds. The user can terminate the process at any time. In this case the circled

© 2010 CAD Solutions, LLC

designs in Figures8(e) and 8(f) were deemed satisfactory and worthy of prototyping. The figures shown on the left of Figures 8(g) and 8(h) are the 3D CAD models output from the Geomagic Studio module, while the figures on the right show actual acrylateRP models made on a Multi-Jet Modeling machine (see below).

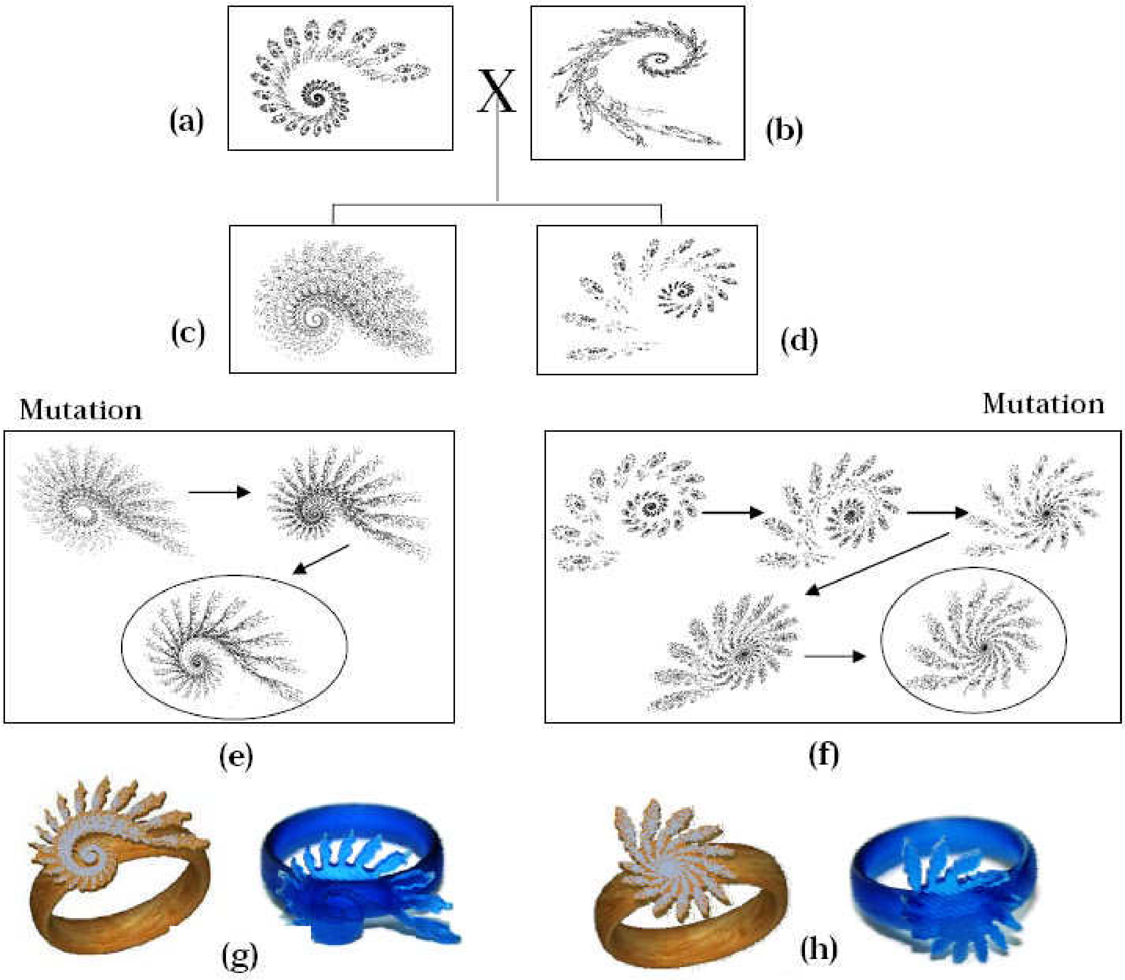


Fig. 8: Example 1 the evolutionary history of the evolved art forms and their CAD and RP models.

In the second example, the selected form shown in Figure8(g) was mated with a new art form shown in Figure9(b). The new off-springs shown in Figures9(c) and 9(d) resulted from breeding with crossover. The second- and the third-best matches to the user's original choice of attributes shown in Figures9(e) and 9(f), respectively, were used to mate with the off-springs formed in the previous step. The user found an appealing form among the off-springs in the third generation of the described process. The selected form is shown in Figure 9(h). The figure shown on the left of the Figure9(i) is the 3D CAD model, while the one on the right is again an acrylate RP model of the selected form. The evolutionary process could, however, be continued.

All blue translucent models shown in Figure8 and Figure9 were fabricated on a RP machine, ProJet™ HD 3000 3-D Production System (Multi-Jet Modeling (MJM) technology produced by 3D Systems, Inc). The material used with this RP machine is an acrylate material (VisiJet® CPX200 wax build material), which can perform like injected wax patterns in the lost-wax casting process.

Therefore the models could be converted directly into metal casts without the need for rubber molds or secondary waxreproductions.

The rough production costs for the rings shown in Figures8(g), 8(h) and 9(i) are estimated by the cost estimating module in *JAFG*. We assume a production batch of forty rings and alost-wax casting process using silver as a casting material. The minimum labor wage rate in the Thai jewelry industry in Bangkok is approximately 250 baht per day (8 hours) or $0.97 per hour.

After factoring in the prototyping cost, material cost, processing cost and labor cost, the rough production cost of the rings shown in Figures8(g), 8(h) and 9(i) are $16.40, $15.40 and $15.20, respectively. It is, however, difficult to validate the cost model, because most of jewelry companies do not reveal the details of their processes and costs.

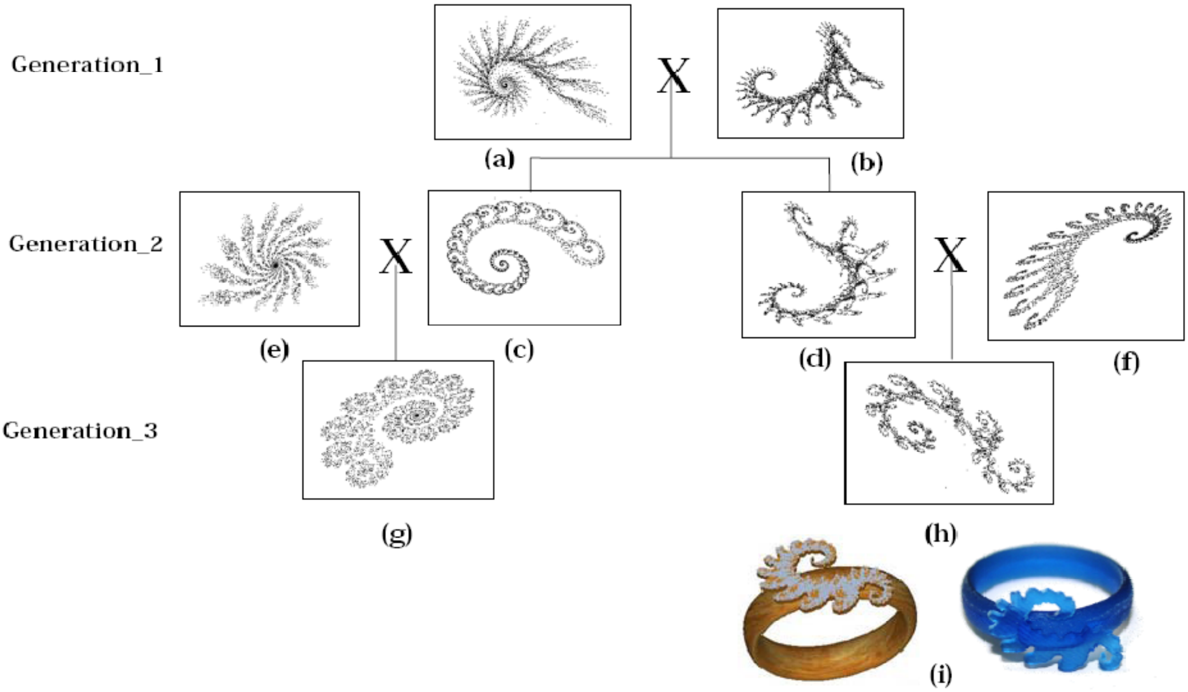


Fig. 9: Example 2 the evolutionary history of the evolved art forms and their CAD and RP models.

4.2 Discussions

We performed two experiments to compare the efficiency of *JAFG* to the previous system [23]. In a first experiment, 48 designs are retrieved from the database based on the set of inputs shown in Table 1 and displayed in a full-screen panel of 8 x 6 images. From these the user picks two of them to be the first parents in the EA. Then the EA generates a new set of designs and the user picks two new parents in each generation. The evolutionary process continues until the user is satisfied with one of the generated designs. The second experiment differsfrom the first on in that the retrieval condition is random, not based on any user preferences.Again the user runs the EA until a satisfactory result is obtained. Both experiments were performed by ten participants, who are master students taking part in a product design class.

For the first experiment, the experimental results show average *JAFG* retrieval times of 39.2s, compared to retrieval times of 38.4s for the previous system. The user of *JAFG* then spends an average of 3313.6s of processing time until a satisfactory design has been obtained, while with the previous EA system users spends an average of 4894.4s of processing time. Thus, the retrieval times of the two systems are almost the same, but the processing time of *JAFG* is less than for the previous approach by about 32 %. In the second experiment, we could not detect any difference between the two systems.

This comparison shows that the case-based reasoning technique using a fuzzy similarity measure does not speed up the retrieval time. But it returns a set of designs that are much closer to a possible final, satisfactory design; thus the user need to go through fewer evolutionary generations. As a result the overall processing time is reduced for *JAFG*.

Eight of ten users prefer the approach of *JAFG.* These users stated that when they began their conceptual designs they sometimes did not know what a final satisfactory design might look like. They just had some vague ideas. The system then provided various alternatives, but many of them in the scope of their stated preferences. When they picked a set of parents from this collection, *JAFG* will generate creative wider variety of acceptable forms compared to the previous approach.

The size of the current design database (300 designs) does not pose a problem with respect to retrieval time. But when the number of cases in the database increases to several thousand designs; the efficiency of the retrieval process becomes an issue. It could possibly be improved by using a different similarity function. So far our research has focused on the triangular similarity function. Other membership functions, such as trapezoidal or Gaussian, also look promising and will be studied in the future.

The user interface plays an important role in such an interactive system. In *JAFG* it was designed to accommodate novice users and to make it easy to input the initial design preferences and to control the evolutionary process. It is also easy to specify the fabrication information for the final prototypes. The user can input the information through the scroll bars, dropdown menus, command buttons, checkboxes and option buttons; this informs them of the available choices and avoids typing mistakes. But improving the user interface even further is an ongoing quest.

5 SUMMARY

This paper presents an interactive intelligent design system that is driven by computational aesthetics for jewelry design. The prototype system '*JAFG* Jewelry Art Form Generator' extends the capabilities of previous CAD tools to include the conceptual design phase. Our prototype system demonstrates the following features:

- Efficient search through the collection of previous designs for examples that match best the stated design preferences, yet maintaining a good variety of design options.
- Interactive control of an evolutionary algorithm to generate a rich set of alternative shapes/forms that adhere to the original design specifications.
- Calculating a rough cost estimate at an early stage of the design process.

The system is structures in three layers to support the designer from the conceptual design phase, through evolutionary improvement, to the final model-making stage. The computational infrastructure of the system employs case-based searching with a fuzzy similarity measure, interactive evolutionary algorithms, and rule-based reasoning.

Art forms are represented using IFS fractal geometry. Genetic operators (mutation and crossover) are used to create new and diverse forms. *JAFG* offers, to jewelry designers, the possibility to explore broader design alternatives. It can also be further developed to work as an electronic design catalogue. The same approach should readily be usable for other non-functional designs such as ornamental decorations of products that can increase a product's attractiveness and value.

ACKNOWLEDGEMENTS

The research was supported by the Naresuan University Research Fund under Contract No. R2553C266. I would like to gratefully acknowledge Assoc. Prof. Erik L. J. Bohez and Dr. KittinanUnnanon, for constructive suggestions to this research. I would like to gratefully thank to Prof. Carlo H. Séquinfor his thorough help in correcting and improving my manuscript.Grateful thanks go to the National Science and Technology Development Agency (NSTDA), Ministry of Sciences, Thailand, for providing Geomagic Studioand Magics software for this research.We also thank Mr. PisitponAroontat and Comgraph Co., Ltd. for manufacturing the RP models. Special thanks go to Dr. FilipKielar for proof-reading of the original manuscript.

REFERENCES

[1] Barnsley, M.: Fractal Everywhere; Academic Press, San Francisco, 1993.
[2] Bentley, K.; Cox, E. J.; Bentley, P.: Nature's batik: a computer evolution model of diatom valve morphogenesis, Journal of Nanoscience and Nanotechnology, 5(1), 2005, 1-10.
[3] Bentley, P.: Evolutionary design by computers; Morgan Kaufmann, San Francisco, 1999.
[4] Dawkins, R.: The Blind Watchmaker; Penguin Books, London, 1986.
[5] Durkin, J.:Tools and Applications. In Expert System: The Technology of Knowledge Management and Decision Making for the 21st Century Leondes, C. T., Ed.; Academic Press: San Diego, 2002, 23-53.
[6] Gero, J.: Creativity, emergence and evolution in design: concepts and framework, Knowledge-Based Systems, 9(7), 1996, 435-448.
[7] Gonzalez, R.; Woods, R.: Digital Image Processing; Prentice-Hall, Englewood Cliffs, NJ, 2001.
[8] Huntley, H. E.: The Divine Proportion: A Study in Mathematical Beauty; Dover Publications, New York, 1970.
[9] Koile, K.: Formalizing abstract characteristics of style, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 20(3), 2006, 267-285.
[10] Kowalski, Z.; Meler-Kapcia, M.; Zieliński, S.; Drewka, M.: CBR methodology application in an expert system for aided design ship's engine room automation, Expert Systems and Applications, 29(2), 2005, 256-263.
[11] Ong, L. S.; Narasimhalu, A. D.: Chapter 11 Case-Based Reasoning. In The Handbook of Applied Expert Systems; Liebowitz, J., Ed.; CRS Press: Boca Raton, FL, 1997.
[12] Poirson, E.; Dépincé, P.; Petiot, J.-F.: User-centered design by genetic algorithms: application to brass musical instrument optimization, Engineering Applications of Artificial Intelligence, 20(4), 2006, 511-518.
[13] Rowland, D.; Biocca, F. The Proceedings of 5th Symp. on Virtual Reality Modeling Language (Web3d-Vrml), VRML '00, New York, 2000, 75-79.
[14] Séquin, C. H.: Virtual Prototyping of Scherk-Collins Saddle Rings, Leonardo, 30(2), 1997, 89-96.
[15] Séquin, C. H.: CAD tools for aesthetic engineering, Computer-Aided Design, 37(7), 2005, 737-750.
[16] Séquin, C. H.: Computer-Aided Design and Realization of Geometrical Sculptures, Computer-Aided Design & Applications, 4(5), 2007, 671-681.
[17] Shehab, E.; Abdalla, H.: An Intelligent Knowledge-Based System for Product Cost Modeling, Int. Journal of Advanced Manufacturing Technology, 19, 2002, 49-65.
[18] Sims, K.: Artificial evolution for computer graphics, Computer Graphics, 25(4), 1991, 319-328.
[19] Todd, S.; Latham, W.: Evolutionary Art and Computers; Academic Press, London, 1992.
[20] Wannarumon, S.; Bohez, E. L. J.: Rapid Prototyping and Tooling Technology in Jewelry CAD, Computer-Aided Design & Applications, 1(1-4), 2004, 569-575.
[21] Wannarumon, S.; Bohez, E. L. J.: A New Aesthetic Evolutionary Approach for Jewelry Design, Computer-Aided Design & Applications, 3(1-4), 2006, 385-394.
[22] Wannarumon, S.; Unnanon, K.; Bohez, E. L. J.: Intelligent computer system for jewelry design support, Computer-Aided Design & Applications, 1(1-4), 2004, 551-558.
[23] Wannarumon, S.; Bohez, E. L. J.; Annanon, K.: Aesthetic Evolutionary Algorithm for Fractal-Based User-Centered Jewelry Design, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 22(1), 2008, 19-39.
[24] Wloch, K.; Bentley, P. J.:Optimizing the performance of a formula one car using a genetic algorithm. In Parallel Problem Solving from Nature - PPSN VIII, Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, 2004, 702-711.

© 2010 CAD Solutions, LLC