Reviews of Computer-Aided Technologies for Jewelry Design and Casting

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***Abstract* – The paper reviews the existing and state-of-the-art computer-aided technologies and computational techniques, which can be applied to jewelry design and casting. A broad array of techniques are selected and ordered into three key parts: design; model-making; and casting, that outline the core of computer-aided jewelry design and casting. Computer-aided design and haptic technologies are surveyed in the purposes of supporting the design of jewelry and shape modeling. Rapid prototyping and computer numerical controlled machines are reviewed in the functions of fabricating physical jewelry models and developing the direct tools. Computer-aided engineering technologies are investigated in the rationales of simulating lost-wax casting process and optimizing process parameters. Artificial intelligence techniques are reviewed in intentions of developing algorithmic designs, and assisting hard computations and parameter optimizations in designing and casting. With those computer advanced technologies, major challenges and solutions are systematically discussed and commented to address new developments for jewelry industry.**

Keywords – Algorithmic design, Jewelry design, Jewelry casting, Computer-aided-design, Computer-aided engineering, Haptic technology, Rapid prototyping.

1. INTRODUCTION

Computer technologies play important roles in soft products such as apparel, furniture, shoes and jewelry whether in design or fabrication to achieve better product quality and fabrication time [1]. Soft product is defined to be different from mechanical parts, which are rarely changed. Soft products are more often adapted and response to the needs of society comparing to engineering and mechanical parts. The design and manufacture of soft products normally concern in ergonomics and aesthetics.

The uses of computer to create soft products are different from solid modeling in conventional computer-aided design system, which is mostly used to create mechanical and engineering parts. Soft products require the uses of computer more on indefinable and intangible aspects such as styling, inspiration, creativity, value-addition, and human–machine interactions. New computer-based techniques need to be developed in order to facilitate these soft product design and manufacturing.

Fashion design is an applied art that is dedicated to the design of clothing and lifestyle accessories including jewelry. Jewelry is created within cultural and social influences of a specific time. Jewelry becomes a part of human civilization and it is considered as one of the motivating soft products [1]. Some types of jewelry are considered as fashionable product, which is a type of soft products. Fashionable product [2] is a product of social demands, rapidly adapted to human's needs, and concerned in their aesthetics and is used in decorating on human's body.

In the digital age, computers become designers' assistants that support design management and activities along design process such as collecting examples, data, and information, creating new design ideas (solutions) based on design contexts and constraints and/or customer requirements, including design evaluation and selection. Miner *et al*. [3] presented an idea in the wearable technology form based in jewelry design called "Digital Jewelry". They proposed the future of wearable pervasive devices, which not only meet users' functional requirements but also social, emotional, and aesthetic needs.

In this paper, jewelry design and making is considered in the case of mass production. It is an industrial design product and also fashionable product, which needs the integrations and harmonies among art, science, and engineering. Computer technologies help jewelers in integrating design, model-making, and production in line that can shorten time-to-market, and provide consistent product qualities.

This paper is aimed to provide the information of the recent computer-based technologies, which can be applied to jewelry design and fabrication. These computer technologies can be applicable in other industrial design products including soft products. Jewelry is a good example for demonstrating the integration among art, science and engineering. Jewelry making is not only solely based on art, but it also, in fact, needs the understandings and fundamental of material science, manufacturing process and engineering techniques.

To clearly describe the reviews of computer-aided technologies for jewelry design and casting, the overview of the review process is illustrated in Fig. 1. The jewelry design and casting processes are divided into three main parts: design; model-making; and lost-wax casting. In the first part, Computer-Aided Design (CAD) is surveyed for the purpose of designing jewelry and supporting design

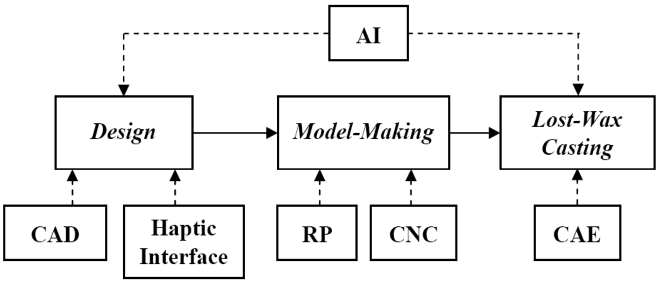


Figure 1 Overview of the review of computer-aided technologies for jewelry design and casting

tasks. Furthermore, in this part the paper reviews haptic technologies for the same purpose of CAD that is designing jewelry, but they have different shape modeling techniques. The second part is model-making; Rapid Prototyping (RP) and Computer Numerical Controlled (CNC) machines are reviewed for the purpose of rapid model-making process, which can be integrated into design system. Lost-wax casting is in the third part, which is the production part; the paper provides the reviews of Computer-Aided Engineering (CAE) applied to simulate the process of jewelry lost-wax casting for monitoring the behavior of molten metal and the formations of defections in the process. Artificial Intelligence (AI) techniques can be applied to assist computations and optimizations in designing and casting.

The paper is organized into 7 sections. In the first section, the state of problems, the objectives of the reviews, and the overview of review process and related computer-aided technologies are introduced. The section 2 provides the basics processes of jewelry design, model-making and production. The section 3 provides the reviews of the roles of computer-aided technologies for jewelry design, which includes CAD, mathematics in jewelry application, and haptic technologies. The section 4 describes the applications of RP and CNC machines in jewelry model-making. The section 5 explains how CAE is applied in jewelry casting and its benefits. Artificial Intelligence techniques applied in product design and castings are discussed in the section 6. The last section concludes the roles of the advanced technologies in jewelry design, model-making and casting, and also provides the future directions of developments in jewelry industry.

2. JEWELRY DESIGN AND MAKING

Before beginning the discussions on the advanced technologies in jewelry design and making process, this section provides the introduction of jewelry, and the information of jewelry design and jewelry making processes.

2.1 Jewelry

Jewelry is one of the oldest forms in decorative art [4], which may be traced back to over than twenty-thousands years ago. The early jewelry was necessary for survival and also had association of protection. Over time with the skill development of artisans and metal smiths they were kept busy making tools, containers, weapons and jewelry. The restructuring of society led to the era that used jewelry to announce the wearer's wealth and social status. The long history of jewelry can be found in [4].

Up till now, jewelry has been made to decorate body parts such as hairpins, earrings, necklaces, rings, brooches, bracelets, etc. Jewelry is regarded as a way to express wearer's style, taste, and social status and also provides some functionality.

There are many types of jewelry. High-quality jewelry is made with precious metal such as gold, silver, platinum, etc, and gemstones. Nowadays, there is growing demands for art jewelry where design and creativity is more essential than material value. Costume jewelry more depends on fashion. It is less costly, made from lower value materials and mass-produced.

2.2 Jewelry Design

There are several principles of jewelry design, however, among them the major importance considerations are as follows: fitness to purpose, unity between stone and ornament, conformity with personal characteristics of the wearer, conformity with costume, nature and distribution of motifs, and limitations and possibilities of metal as a medium of expression [5]. Inspiration for jewelry can come from everywhere whether natural objects or human-making objects.

Jewelry design is an iterative process, which typically begins with the design concepts. Design concepts may be originated by customer or designer.

In the first case, customer provides design concepts to designer. Then the designer design jewelry products according to those design concepts and make design sketches, the number of design sketches varies on case-by-case. After the designer finished the sketches, the sketches are selected by marketing person to present to the customer. After one or more design sketch was chosen by the customer, the designer gives the details of the chosen design. This detailed design provides the geometric information of the features and objects in the design, which is further used in model-making. In this stage, the designer makes discussions with model-maker on the details of the design and manufacturability. Therefore, in some case the modifications of the design are needed to be easier handled in the successive production processes.

For the second case, jewelry corporate creates the concept of design collection himself. Then designer freely creates the designs and makes design sketches, the number of design sketches varies on case-by-case. Design team selects the favorite design, and then the designer makes the details of the selected design to be used in the discussion with model-maker and engineer for the manufacturability, then it might be required some modifications. After the selected design was finalized, the jewelry model is produced and used in the successive processes.

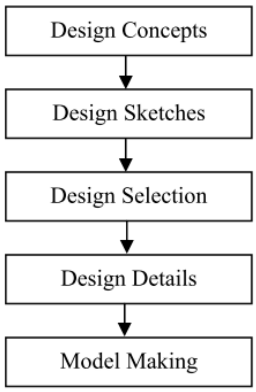


Figure 2 Jewelry design process

The generic jewelry design process is illustrated in Fig. 2. Further information of jewelry design process can be found in [6].

2.3 Jewelry Making

Jewelry making process begins with the creation of a jewelry master model or prototype, illustrated in Fig. 3. In general, the master models for jewelry casting can be made of either metal or wax depending on design complexity, size and shape of jewelry, and skill and intent of model-maker.

Metal models can be made from brass, tin, silver, etc, as shown in Fig. 4(a). They typically are made for making raw rubber mold. While wax models typically are made for one-of-a-kind jewelry pieces or as the original model for casting a metal model. To duplicate wax patterns (shown in Fig. 4(b)) from the wax models, molds can be made of silicone, because silicone mold can be made under room temperature, while rubber mold is made around 150 °C in the vulcanizing process. Rapid prototyping technologies were applied for fabricating jewelry prototypes in shorter time, the details of RP are further explained in Section 7. The rubber or silicone molds are used to reproduce wax patterns of the jewelry model by using wax injector. The wax patterns are welded on a wax rod to assemble a wax tree. The wax tree is then attached to the center of the dome of a sprue former. A flask is covered and fixed on the sprue former.

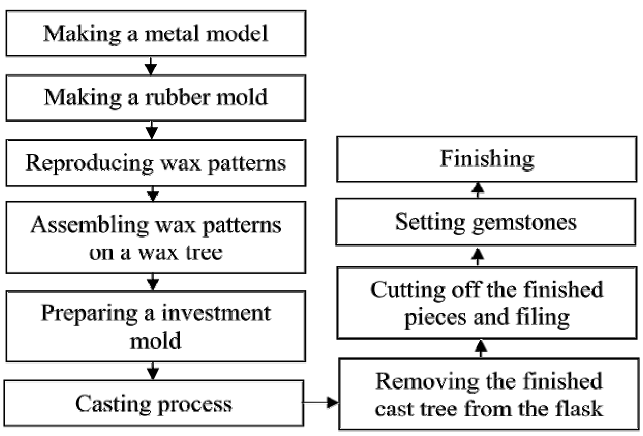


Figure 3 Jewelry making process

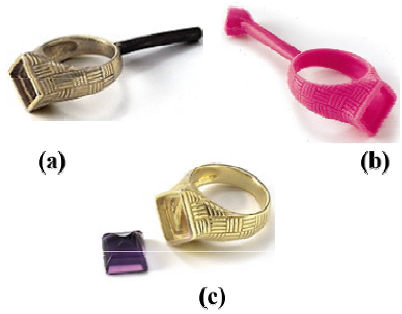


Figure 4 (a) brass model; (b) wax pattern and (c) ring and gem

Investment is prepared and poured into the flask under vacuum environment to remove air bubbles. After about 20 minutes the flask is set.

The flask is placed in a kiln with the sprue opening facing down and heated to 700 °C with the temperature increments of 100 °C per hour; this process is called burn out cycle. The wax tree inside the flask is then melted out. After the burning cycle was completed, the flask now is an investment mold. In general, the flask will be kept in the kiln about 7 hours before casting. The final temperature of the flask should be approximately 550 – 700 °C, depending on the shape and size of jewelry products.

The flask is placed in the casting machine at about 50 °C above half the melting point of the alloy. There are 2 methods of jewelry casting: by using centrifugal force and by using vacuum force [7]. The amount of metal required for casting can be determined by a comparison with the density of the metal to be cast to the density of the model. The metal is poured in a crucible, which was placed in the casting machine. Here the metal is melted and heated to the casting temperature, and then poured into the flask.

After the solidification of the metal was completed, the flask is moved out from the casting machine. The finished cast tree is then removed from the flask by water injection. The jewelry pieces are cut off and filed. Gems are then set on them as, shown in Fig. 4(c). They would be completed after finishing process. Jewelry making process is described in more details in [7-8].

In fact there are still several techniques needed for making jewelry model (shown in Fig. 5), which are the same techniques for making one-of-a-kind jewelry. The techniques used in fabrication basics are sawing, piercing, filing, carving, drawing wire, melting, etc. The techniques used in making connections are riveting, fusing, soldering, etc. Forming techniques are forging, bending, die forming, electroforming, etc. Texturing techniques are hammered marks, roller printing, etching, chasing and repoussé, granulation, etc. Mixed metal techniques are lamination, solder inlay, marriage of metal, kum boo, mokume gane, etc. Other techniques and details can be found in [9-10].

Figure 5 Examples of jewelry making techniques (a) electroforming [11]; (b) chasing and repoussé [12]; (c) granulations [13]; (d) mokume gane [14] and (e) kum boo [15]

3. Computer-Aided Technologies in Jewelry Design

3.1 Computer-Aided Design

Computer-aided art and design tools play a key role in the entire development process, helping artists and designers from the initial conceptual ideas, through the optimization of the design parameters.

Most of CAD systems apply either solid modeling method or surface modeling method for representing three-dimensional (3D) models with Euclidean measures. Solid modeling provides the most complete representation compared to other methods [16]. A solid model can describe shape and material properties of the object. While surface modeling provides a convenient way to model freeform curves and surfaces [17]. Non-uniform rational basis-spline (NURBS) allows a modeling system to use a single internal representation for a wide range of curves and surfaces as well as intricate piecewise sculptured surfaces [18]. The robust modeling systems have been developed based on NURBS for computer-aided design of aircraft, automobile, shoes, jewelry, bottles, etc.

Designing jewelry by computer was first investigated by [19]. Rings were modeled by using CATIA software [20]. Several general CAD software nowadays are more popular in jewelry design such as Rhinoceros [21], SolidWorks [22], AutoCAD [23], etc. Some examples are illustrated in Fig. 6.

There are many CAD commercial software packages specifically developed for jewelry design such as JewelCAD [24], RhinoJewel [25], ArtCAM JewelSmith [26], Matrix3D [27], SoluTech-3D [28], etc.

Most of them are parametric and feature-based modeling system. Those software offer graphical user interfaces and realistic rendering capabilities. They provide various CAD modeling tools for simply modeling jewelry pieces. The special feature of such systems is the built-in libraries of standard rings, cut gemstones (shown in Fig. 7 and 8), jewelry findings, and a set of collections of popular items.

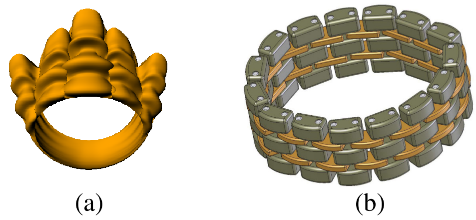


Figure 6 Jewelry pieces modeled by (a) Rhinoceros [21] and (b) SolidWorks [22]

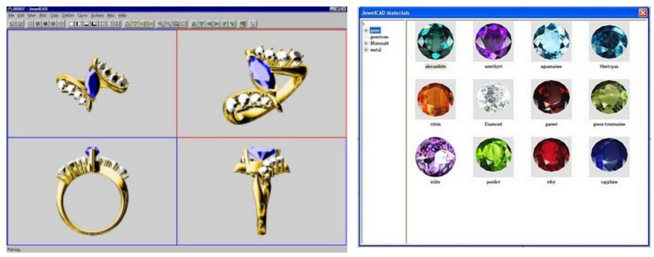


Figure 7 Examples of some features in JewelCAD [24]

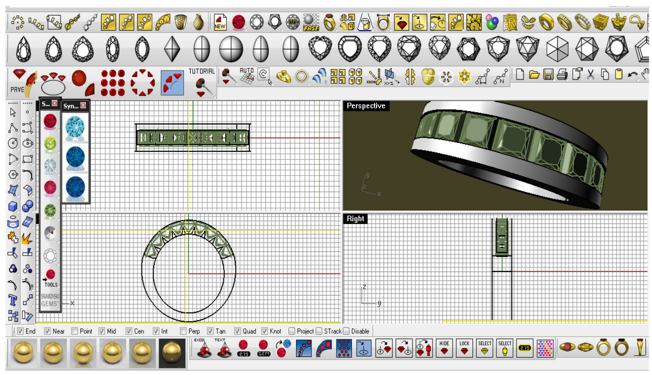


Figure 8 Examples of some features in RhinoJewel [25]

They also provide the capability of exporting models directly to rapid prototyping and computer numerical control mill/cutting machines. The other special features is such as Matrix3D [27] offers builders for recording design steps and for defining part parameters to be used for fabrication.

In jewelry design process, conceptual design is an early stage that has influences in characters of products. 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. 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.

The advantages of the uses of CAD in design include easily editing and redesigning, easy in manipulations in shape transformation, supporting in integration into manufacturing stage.

Although several CAD systems are applied for supporting the activities in product design of various industries including fashion design, some crucial efforts have still to be faced when using these CAD systems. The efforts lead to the new developments of 3D modeling paradigms, which give more emphasis on the creative phase of aesthetics and styles for soft products. These systems require less dimensioning and patterning, but offer advanced functionalities for easily modifying shapes.

3.2 Mathematics and Algorithms in Art and Design

Mathematics and art have a very long historical link since the ages of the ancient Egyptians and ancient Greeks [29].

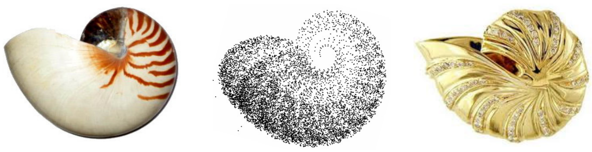
A geometry known as golden ratio or golden section [30] was used in famous ancient architectures such as the Great Pyramid, Parthenon, Colosseum, Gothic master plan and famous paintings of well-known artists such as Leonardo da Vinci, and Michaelangelo.

Organic shapes found in nature like sunflower, snowflake, fern, ***Nautilus*** shell are creative intelligence as beauty of nature. They can be modeled by fractal geometry [31]. There are many types of fractal geometry, for instance, iterated function system (IFS) [32]. Fractal geometry is usually used in computer graphics for texture visualization. Their strengths are good in image compression with small space consumption, and easily encoding and decoding.

Several researches employ these advantages to be used as form representation [33-43] in modeling artistic works, for instance, jewelry design [33, 41-45], furniture decoration [33], wallpaper design [34], textile design [36], sculpture [40]. An example of fractal modeling applied to design Nautilus shell pendant is shown in Fig. 9.

Condensation set [31] is a theorem of iterated function system (IFS), which can create new patterns based on an existing one, by repetitions and affine transformations. This technique can be applied in jewelry design [41-42] (shown in Fig. 10) and other decorative design.

Several examples of the uses of mathematics in art and design 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 for sculpture design, as shown in Fig. 11.



(a) (b) (c)

Figure 9 An example of fractal modeling applied to jewelry design (a) Nautilus shell [46]; (b) Nautilus shell modeled by IFS fractal [42] and (c) Nautilus shell pendant [47]

(a) (b) (c)

Figure 10 An example of applying condensation set to design jewelry [42], (a) a star-like shape; (b) a pattern created by applying a condensation set and (c) jewelry ring designed using the condensation set

His work can demonstrate the roles of computer-aided design tools in the creation of geometrical shapes, shape optimization and aesthetic considerations [48-50]. His works can be applied in jewelry design.

Pierced Byzantine jewelry (shown in Fig. 12) is a kind of late ancient jewelry during the period 3^{rd}–7^{th} century A.D. It was made from thin sheets of gold. The design patterns were made by piercing and engraving with a thin sharp tool and decorated with triangular carvings using an iron chisel [51].

ByzantineCAD was developed by Stamati and Fudos [52]. It is a parametric CAD system for supporting the design of pierced Byzantine jewelry. Pierced jewelry is modeled using voxel-oriented feature-based CAD approach. A large complex pierced jewelry was modeled by appropriately scaling and placing elementary structural elements, as shown in Fig. 13.

Figure 11 (a) Monkey Trefoil [48] and (b) Small bronze model of Solar Circle [49-50] generated by Sequin's program

Figure 12 Examples of Byzantine jewelry [52]

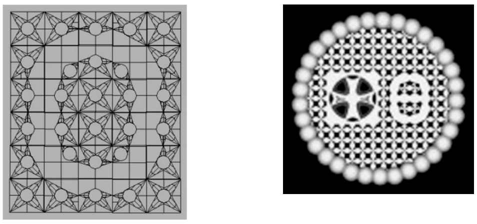


Figure 13 Example of (a) structural elements and (b) a solid model of pierced jewelry modeled by ByzantineCAD [52]

The other type of jewelry that can model using mathematic approach is Celtic jewelry. Celtic jewelry, as shown in Fig. 14, is made up from Celtic knots, which are a variety of (mostly endless) knots and stylized graphical representations of knots used for decoration, used extensively in the Celtic style of insular art [53]. These Celtic knots are popular in jewelry design, because of their characteristics, meaning, and Christian's belief. Celtic knotwork is an ornamental art style, which intertwined cords draw complex and well-structured designs to fill a given area. These designs consist of cords with an alternating weave. Artist can create complex designs from as few cords as possible. More details of Celtic knot can be found in [54].

Browne [55] had proposed a technique based on Cantor division used to decorate artistic knotwork designs. Some examples are shown in Fig. 15 and 16.

Wild knots are investigated as an decoration to the Celtic style of ornamental knotwork in [56]. The wild knot designs are constructed by the recursive application of a simple generator set of pre-defined cord segments, where their end points satisfy certain geometric constraints.

With these principles and the traditional knotwork technique of N-interlacement, they are used to decorate a design and add complexity, as shown in Fig. 17.

Figure 14 Examples of Celtic jewelry [57]

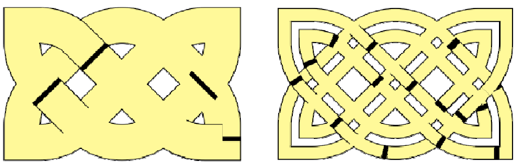


Figure 15 A Celtic knot (left) and its double-interlaced counterpart (right) [55]

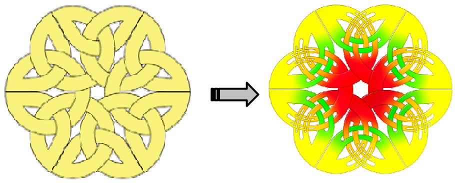


Figure 16 A decorative pattern (right) woven at levels 0, 1 and 2, with source knot (left) [55]

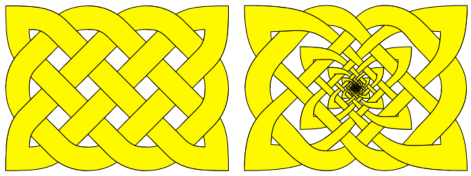


Figure 17 A simple Celtic knot (left) and a wild knot based on the same design (right) [56]

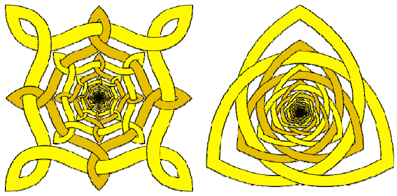


Figure 18 Two designs of tame fractal knotworks [56]

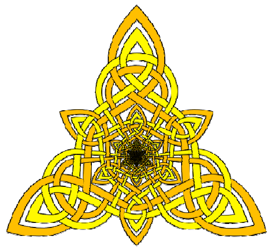


Figure 19 A hybrid wild fractal 2-interlaced knotwork design [56]

Tame fractal knotwork design [56] is constructed from tame knots without attachment points, and the interaction between levels gets through inter-leavement of the tame cords at successive levels. The tame fractal links do not require a special outer frame as all levels are identical, apart from rotation and scaling, shown in Fig. 18. An example of hybrid wild knot technique and N-interlacement is shown in Fig. 19.

However, none of available CAD system is developed for designing and modeling Celtic jewelry. It is very interesting to develop algorithm as mentioned above to create Celtic knot in CAD system.

Guy and C. Soler [58] proposed an algorithm for rendering faceted colored gemstones in real time based on the analysis of optical phenomena, their simplification and their adaptation to a hardware-based implementation. The rendering speed of the proposed system offers the possibility for observing gemstones that the viewpoint can be changed in real time, including the stone physical properties and geometry.

Parametric feature-based modeling approaches using mathematics or algorithms mentioned above offer the capabilities of feature's parameter handling and can easily apply to high level of CAD system and Artificial Intelligent (AI) based design system. These mathematic arts can be developed as algorithmic design.

3.3 Haptic Technologies in Jewelry Design

In the digital age, virtual prototyping becomes a popular technology in design and validation in various industries. Virtual prototypes are less expensive compared to physical models. They are easily configurable and support variants. They allow for several simulation runs on a single model and reduce the overall number of physical models used in entire product lifecycle. The recent trend aims to use virtual prototyping earlier in conceptual design stage in order to evaluate design concepts, improve product quality, and facilitate designers' activities [59].

Haptic technology is one of the most advanced virtual prototyping systems, which offers an innovative approach for combining physical and digital aspects to be used in various phases of product design and development. The development of haptic modeling is based on physical laws. Haptic interaction is developed to be a natural link between virtual world and practical applications. For instance, in a developed system, a haptic device is used as the central mechanism for shape modeling, reverse engineering, real time mechanism property analysis, machine tool path planning and coordinate measuring machine tolerance inspection path planning [60]. Using the force feedback in the mentioned activities, as a result, the product development process is more intuitive, efficient, and user-friendly. PHANTOM® marketed by SensAble® Technologies [61] was used in this work [60].

Haptic rendering allows users to feel, touch, and manipulate virtual objects through a haptic interface in simulated environment [62-63]. Haptic rendering algorithm is developed for computing the correct interaction forces between the haptic interface representation inside the virtual environment and the virtual objects. Haptic rendering algorithms also guarantee that the haptic device correctly renders such forces on the human operators. The haptic interface is virtually represented via an avatar, which a user can interact physically with the virtual objects in the virtual environment. The selection of type of avatar depends on the capabilities of haptic device and simulation applications. The developer may choose volumetric object exchanging forces and positions with user in a 6-dimenional space.

Haptic rendering techniques are reviewed in [63-65]. In general a haptic rendering algorithm [63] consists of three main parts: collision detection, force response and control algorithm, as illustrated in Fig. 20.

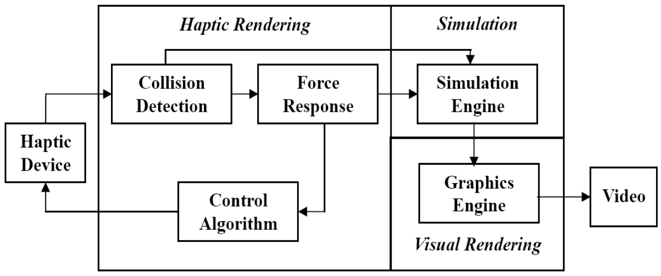
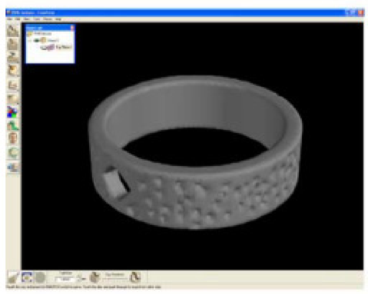


Figure 20 Haptic rendering divided into three parts (modified from [63])

There are several types of haptic interaction method used in simulations depending on the applications to render 3D objects. The basic process associated in haptically rendering objects in virtual environments with force feedback device [65]. When user manipulates the probe of haptic device, the new position and orientation of the probe is sensed by the encoders. Collisions between virtual objects and simulated stylus are detected. The reaction force is estimated by using the linear spring law and reflected to the user via the user interface.

The followings are the discussions on how haptic technologies applied to art and design including jewelry design. Haptic modeling system allows designers to utilize their manual skills for intuitively interacting (touch, feel, manipulate and model) with 3D virtual models in the virtual environment, which is similar to natural settings. In general, shape modeling can be divided into three operation types: material addition, material removal and texturing. An example of jewelry design [60] is shown in Fig. 21 using Freeform® software (a commercial shape modeling software developed by SensAble® Technologies) and PHANTOM® haptic device [61] is shown in Fig. 22. When a user uses a virtual tool such as a ball-end milling cutter for removing material from a workpiece, the user can feel the physical realistic occurrence of the material with force feedback during the process. The modeling process procedure is decomposed into unit machining operation. The parameters are recorded and can be changed later. The model will be regenerated after parameters change [60].

(a) Sketch of a pattern on a ring surface



(b) Texturing by sculpting in Freeform

Figure 21 Three-dimensional jewelry design modeled using haptic device [60]

Figure 22 Haptic devices produced by SensAble® Technologie [61]

Most of haptic modeling applications are based on volume representation. Some applications have been developed with providing haptic interaction with volume dataset without providing force feedback. Some works are more related to physical-based shape modeling. Some sculpting systems developed based on haptic force associated with dynamic subdivision of solids that provide users the illusion of manipulating semi-elastic virtual clay [66].

Haptic shape modeling is presently suitable for conceptual and industrial design rather than engineering design, because the current haptic systems lack a user-friendly parameter-driven mechanism [60].

Haptic rendering offers users the feeling experiences of virtual objects in a virtual environment. Haptic rendering algorithms therefore approximate precise interaction forces between haptic interface representation inside simulated environment and virtual objects inside the environment [63]. Applications of haptic rendering are popular in medical, surgical and dental operation training [67-70], art sculpting [71-72], conceptual design modeling [73-76], and product design system [69, 77-81]. Most of haptic rendering methods applied to those applications are based on tool contact simulation, surface tracing and object cutting, while the force models are based on elastic deformation.

Reverse engineering is a modern design process that generates a CAD model of either an existing physical object or some part of object, by using digitizing methods to collect point clouds of the surfaces of the object to segment the point clouds, and fit them to the different surface features. Yang and Chen [72] proposed a reverse engineering methodology based on freehand haptic volume sculpting method. Their method can be used for conceptual design and helpful in the sculpting process to guide user to remove the dangling volumes.

The five-axis haptic jewelry design and manufacturing system was developed by Sukkromsai *et al*. [79]. The system offers the tool path generator that can automatically generate the 5-axis machine's toolpath through the movement of a haptic finger on a virtual workpiece. The generator then creates a set of standard motion of a cutting tool. The overview of 5-axis haptic jewelry design and manufacturing system is shown in Fig 23.

Chen and Tang [81] developed a haptic system, which offers the interactive modification of cutter orientation during five-axis finishing cuts in order to improve the surface finish quality and collision avoidance strategies.

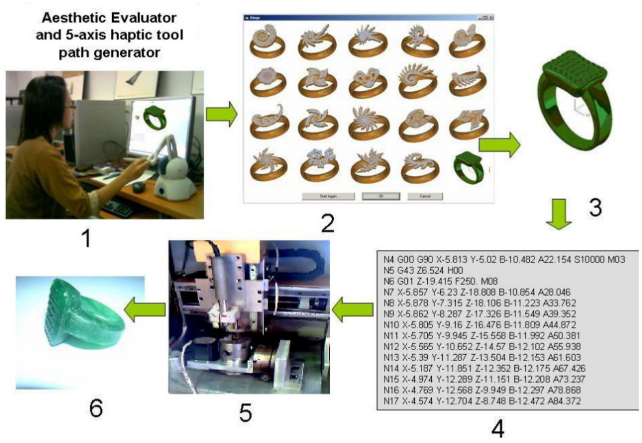


Figure 23 An example of haptic cutting application in jewelry design [79]

The developed system can support two haptic models, which supply three degrees of freedom force feedback and six degrees of freedom posture sensing. Their system can be extended to various industrial product designs.

Until now, there are quite few researches, which applied haptic technology in jewelry design and making. By combing haptic device with the traditional skills of jewelry designers and model makers, it offers benefits of more natural ways of working such as hand modeling with digital models.

4. Computer-Aided Technologies for Automatic Physical Jewelry Prototyping

The advanced technologies such as Rapid Prototyping (RP) and Computer Numerical Control (CNC) machines play important roles in making jewelry models. Rapid prototyping is a process of automatic construction of physical objects, which is based on additive manufacturing technology. RP are widely used to fabricate models and prototype parts in various applications. RP are even used to produce production-quality parts in relatively small numbers and complex shapes and sculptors for fine arts. RP is also used in jewelry model-making [43, 82]. It can reduce time in model-making stage. It can be used as injected wax patterns in direct casting in which production time is significantly reduced. Some RP ring examples are shown in Fig. 24.

Bohez [83] demonstrated the used of five-axis machining in various applications including jewelry. He discussed on the benefits and disbenefits of five-axis milling. The machined jewelry objects can be used as either a master model for wax reproducing or finished products. By this ways, it can reduce production time.

5. Computer-Aided Engineering in Jewelry Casting

Jewelry casting is one of the most difficult processes in handling the casting quality and defects. As well as the casting materials are precious alloy, which possibly cause high production cost in term of casting defects.

Figure 24 Examples of RP objects of jewelry design [43]

Computational Fluid Dynamics (CFD) and numerical simulation have applied to various applications in different industries, because they can help casters to comprehend behaviors of casting processes and to reduce production cost and time, which are caused by casting defects.

Within this decade, CFD and numerical simulation were applied to jewelry manufacturing process; they was proved that they have potential to work as a tool in preventing casting defects [84-87]. However many aspects need to be further studied: the study of the precious alloys' physical properties and of investment materials including the investigation of the dynamics of the investment casting process.

Therefore CFD was applied to simulate the investment casting of jewelry products [88]. The numerical simulation software used in this research was FLOW-3D [89]. The basic concept of the software is to solve Navier-Stokes equations in a discrete fashion with a control-volume method. It is used to optimize and fine tune the process parameters, which are based on the thermal and chemical properties of mould material used and casting precious alloy used. There are several CFD software packages available such as FLOW-3D, MAGMASoft [90], ProCAST [91], etc. Some interesting features of them were compared in [92]. The applications of CFD are shown in Fig. 25. Some casting simulations are shown in Fig. 26-27.

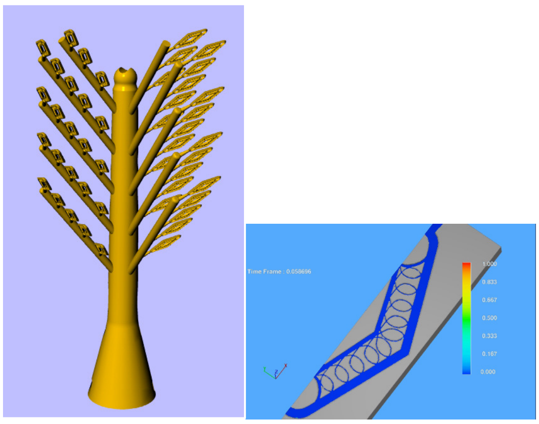


Figure 25 An example of a simulation of filigree casting using FLOW-3D [85]

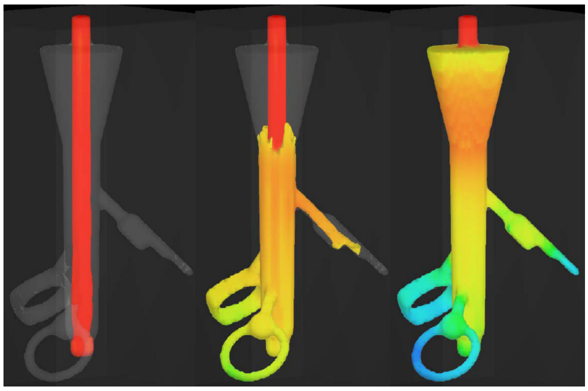


Figure 26 The simulated filling using FLOW-3D [92]

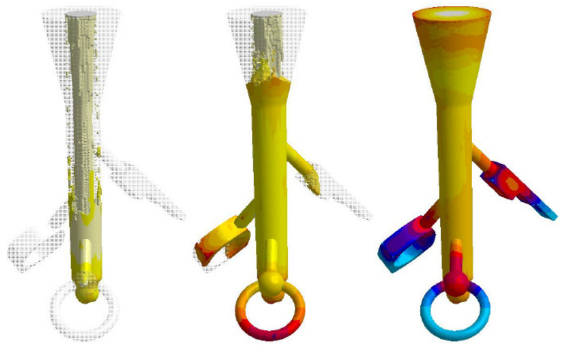


Figure 27 The simulated filling using MAGMASoft [92]

6. Artificial Intelligence in Design and Production

Artificial intelligence (AI) is a branch of computer science dealing with the reproduction or mimicking of human-level thought in computers [93].

The researches in "AI in Product Design" area aim to understand human creativity in product design by mimicking it in computer [94]. Therefore, in AI, hypotheses about knowledge and reasoning are derived from assumptions or observation or study, and then used for building systems (as computational model). This is a good way to investigate and understand the human intelligent activities. These computational models are expected to provide reasonable clarifications of design reasoning, and to be consistent with observations [94].

Nowadays, AI plays an increasingly key role in design applications. AI has been widely used in different stages in product design process, for example, customer needs identifications, concept generation, concept evaluation, shape optimization, design parameter optimization, and design evaluation, and other decision systems.

The popular AI techniques applying to product design are such as Expert Systems (ES), Evolutionary algorithms (EA), fuzzy logic or fuzzy set, and Artificial Neural Network (ANN). The applications of AI in the different stages of product design process are explained in the following sections.

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 can explore more design alternatives. Most of the evolutionary art and design systems generate new forms based on some random initial population. Each individual of the population would be evaluated for its fitness by a human artist or by a computer (computational model). The user interface is designed to assist designer to easily evaluate 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 overview of general evolution process in EA is illustrated in Fig. 28.

The major elements of an EA in design are described as follows and simple evolutionary algorithm [95] is illustrated in Fig. 29.

Genotype is a genetic code representation that contains all information for generating a specific individual. Genotypes are typically encoded in the chromosome strings 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 generation of offspring are 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 offspring 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.

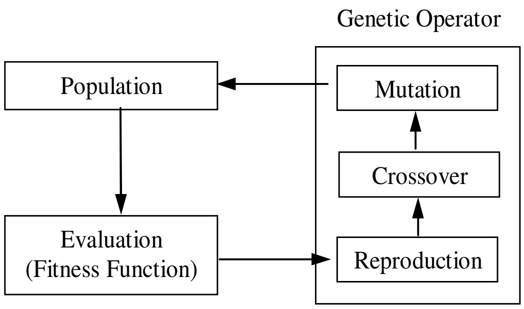


Figure 28 Overview of general evolution process in evolutionary algorithm.

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 [95], 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 [95], 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 role in controlling the evolutionary process. There have been several researches demonstrating the use of EA in design applications, including the creation of artistic forms. The first artificial aesthetic evolution based on a computer program is "Biomorph Land" developed by Richard Dawkins in 1986 [96]. His computer program allows users to conduct the evolution of generations of graphical stick figures. Sims [97] developed a computer program for the evolution of two-dimensional images and described the creation of the complex simulated structures, textures and motions for using in computer graphics and animation, by using the evolutionary techniques such as variation and selection.

Todd and Latham [98] developed an artistic computer program based on natural evolution, mutation and selection as an evolutionary art. Gero [99] analyzed the evolution of creative design and develops a model of creativity and creative design as a form of the computational exploration. He also demonstrated his work in novel floor plan using design knowledge from adapting design cases. Bentley and Wakefield [100] explained how evolution can find incredible and creative solutions to design problems. They removed human from the loop and showed the power of explorative evolution by computer program. They demonstrated their work to the design of table, optical prism and sport car. Rosenman [101] explored the use of evolutionary models as computational models in non-routine design. He generated forms using evolutionary approach based on the growth of cells in a hierarchical organization and demonstrated his work in house design - space generation.

Eckert [102] proposed an interactive evolutionary design system for concept design applied in knitwear industry to facilitate garment shape design. In this work, forms are represented by Cartesian coordinates jointed with straight lines and Bezier curves, and color scheme for modeling two-dimensional garment parts. Cho [103] developed an evolutionary design system for clothes and apparel design. The system is used for generate three-dimensional arm and sleeve part, neck and body part, and skirt and waistline part forms. Grundler and Rolich [104] developed an evolutionary algorithm aided design for textile design. The algorithm can generate two-dimensional fabric patterns made from yarn color matrix and weave matrix.

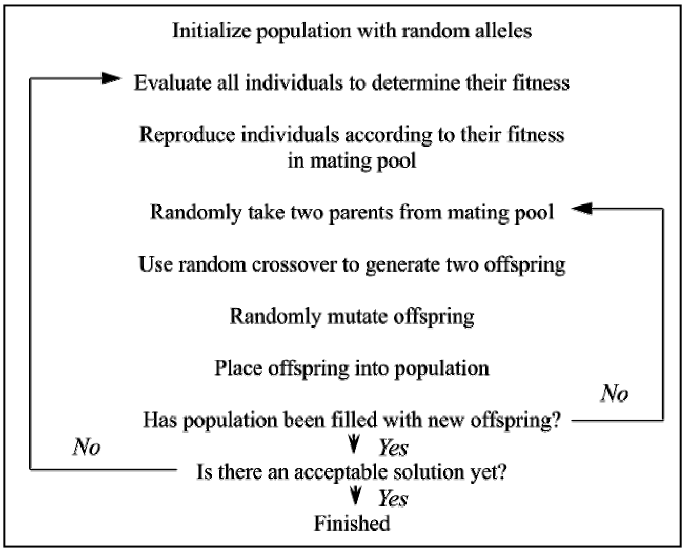


Figure 29 Simple evolutionary algorithm [95] with minor modifications

Unemi [105] developed a computer program based on evolutionary algorithm for breeding expression-based images, abstract images and short musical pieces. Machado *et al.* [106] developed a computer program that works as evolutionary artificial artists. Their programs created expression-based images and abstract images.

Wannarumon and Bohez [41] introduced an evolutionary design approach for the creation of non-functional art forms for jewelry design. These art forms are modeled using fractal geometry generated by iterated function system (IFS) [31]. The design system was later improved the evolutionary algorithm and fitness functions [42]. The interactive evolutionary design system is specifically aimed at novice users since it employs a user-centered design approach. It also provides an enhancement of the resulting algorithmic aesthetics. Wannarumon [43] improved the design system by integrating ES and EA into the prototype design tool named *JAFG* (Jewelry Art Form Generator). Case-based reasoning method and fuzzy logic are used for calculating case similarity to increase the efficiency of existing art forms retrieval. A rule-based reasoning with a forward chaining IF-THEN rule method is applied to estimate production cost.

Pang and Hui [45] proposed an interactive evolutionary design system, which uses 3D fractal art form as form representation. They applied their system in jewelry design and decorative patterns applications.

There have been many publications demonstrating the use of EA systems in design applications, including the creation of artistic forms, e.g. [107-112].

ES [6] and EA [42] 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 [43]. 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 [41-42]. The main objectives are to provide more variety in the designs and to reduce the overall processing time of the system. Rough production costs are also derived and stored in the cost estimating module of the system. This helps the 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.

In general, product design process begins with identifying customer needs, concept generation, concept selection, evaluation, and prototyping. Several AI techniques have been applied to assist designers in almost all stages of product design. For instances, customer needs was identified using the concepts of Quality Function Deployment (QFD) and fuzzy set theory [113-114] and fuzzy inference [115]. Product form was automatically created using EA [42, 116-118], fuzzy logic [119] hybrid of fuzzy, neural network and GA [120], and hybrid of neural network and kansei expert system [121]. Fuzzy logic technique was also applied to evaluate and select design concepts [122-125]. Affective user satisfaction was analyzed and modeled using a fuzzy rule-based method [126].

In production, several researches had been applied AI techniques for optimizing process parameters or predicting some consideration properties, which can be applied the concepts to jewelry casting such as the attempt that used GA and ANN in porosity minimization of aluminum casting [127-128], the application of GA in shape and process parameter optimization [129], the optimization of product quality of casts using heuristic search techniques [130] and by using GA and knowledge base [131].

7. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, it clearly indicates that art, science, engineering and technology are able to be integrated to assist artistic creations such as jewelry design and making. The review on computer technologies in jewelry design and prototyping is presented. Jewelry industry can be enhanced for new developments with the advances in CAD/CAE/CNC/RP and virtual reality applications such as haptic technologies. Algorithmic design offers designers for easily manipulating design parameters and automatically generating product forms, and leads to higher level of CAD software. Artificial intelligence techniques have been popularly applied to solve problems in nearly all stages of product design. They employed heuristic techniques for design optimization, design generation, design evaluation and design selection. Haptic technology offers designers for intuitively interactions with virtual CAD models in the virtual environment. CAE is applied in jewelry casting to study the fluid's behavior, defect formations, and process parameter settings. While the advanced technologies such as Rapid Prototyping (RP) and Computer Numerical Control (CNC) machines play important roles in automatic making jewelry models with shorten production time.

From the reviews, the author had summarized the significant progresses in computer aided technologies, which can contribute to jewelry design and manufacturing in three challenging research areas: algorithmic design that can improve the potentiality of CAD for jewelry design; artificial intelligence techniques that can be applied to develop algorithms to improve parameter optimizations in jewelry design and manufacturing; and haptic interface for assisting shape modeling and carving in jewelry design.

8. ACKNOWLEDGEMENTS

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