

# CAD/CAM Methods for Reverse Engineering: A Case study of Reengineering Jewellery\*

Vasiliki Stamati  
Computer Science Department  
University of Ioannina  
GR 45110, Ioannina, Greece  
+30-2651-098825  
vicky@cs.uoi.gr

Ioannis Fudos  
Computer Science Department  
University of Ioannina  
GR 45110, Ioannina, Greece  
+30-2651-098805  
fudos@cs.uoi.gr

## ABSTRACT

Reverse engineering, the process of obtaining a geometric CAD model from measurements obtained by scanning an existing physical model, is widely used in numerous applications, such as manufacturing, industrial design and jewellery design and reproduction. For each application domain we characterize the suitability of various solid models appropriate for CAD. For creating editable CAD models meant for manufacturing we identify that it is more appropriate to use feature-based constraint-based representations, since they capture design intent. We propose this type of model representation for reverse engineering 3D point clouds of jewellery objects. In this paper we propose an approach for reverse engineering of jewellery combining symmetry axes extraction, feature and constraint information exploitation to obtain a more robust and accurate CAD model. First we automatically extract the symmetry axis of the point cloud. Constraints are automatically detected based on these axes and then an iterative interactive process is carried out, during which features are fitted to the point cloud according to constraints. A voxel inspired technique is also employed to describe repeated patterns common to various types of traditional jewellery.

## Keywords

Reverse Engineering, CAD models, feature-based design, constraint-based modeling, voxel-based representation, jewellery design.

## 1. INTRODUCTION

Reverse engineering is the process of obtaining a geometric CAD model from measurements acquired by scanning an existing physical model. The measurements are in the form of 3D point clouds and they correspond to points on the surface of the object being reengineered. Using computer models is very important in various industries because they help improve the quality and efficiency of designs and they also speed up the manufacturing

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and analysis process [18].

Reverse engineering is widely used for various reasons. First of all, by reverse engineering we can obtain the CAD model of a part that is no longer manufactured by its manufacturer or for which only blueprints exist. Also, there are cases where the original CAD model no longer corresponds to the physical part that was manufactured because of subsequent undocumented modifications that were made after the initial design phase. Furthermore, stylists and artists often create models of their concepts using clay, plaster or wood. These real-scale prototypes are then used to create CAD models for manufacturing the objects in an industrial production line.

Section 2 overviews the application domain of reverse engineering. Section 3 presents different models that are used in reverse engineering and examines their appropriateness for the different types of applications. Section 4 characterizes methods that are appropriate for jewellery design and presents a novel design concept for reengineering jewellery. Section 5 offers conclusions.

## 2. APPLICATIONS OF REVERSE ENGINEERING

Reverse engineering methods are used in various applications. They are used widely in mechanical part design and manufacturing for reengineering or replicating existing parts for which no CAD models exist. Works such as [10, 12, 13, 16, 17] have concentrated on creating high accuracy models of manufactured mechanical parts. A characteristic of the objects reverse engineered is that they are usually parts of larger objects and therefore they have to fit and connect exactly with other parts, like pieces in a puzzle. For this reason, the models created through the reverse engineering process should be very accurate.

Reverse engineering is used for applications commonly identified as industrial design, such as the automobile exterior parts design and sculpturing. It is very useful in this field because stylists and artists re-evaluate their designs through real scale models made out of wood or clay, and by having a reverse-engineered CAD model they can easily re-design or modify their designs as needed. Reverse engineering encourages conceptual design because the designer creates an initial prototype, scans it and manipulates it as desired. Reverse engineering is needed for aesthetic design because designing with CAD systems is quite challenging since many free-form surfaces are involved.

Jewellery reproduction is yet another application for reverse engineering. Pieces of jewellery are scanned and re-created so that they can be sent directly to be rapidly prototyped and manufactured. Also, the models created from the initial 3D point cloud can be changed by the user to create modified versions of the initial pieces, therefore expanding the repertoire of jewellery designs from which a user can choose. Furthermore, by reproducing parts of a piece of jewellery a designer can create other types of jewellery to create a matching set. For example, if the initial object is a pendant with a specific pattern, then by reverse engineering the piece we can create other jewellery such as a ring or earrings, to match the original piece. Aside from the above, reverse engineering jewellery gives the ability to modify parameters of the piece according to specific requirements. For example, from the reproduced parameterized model of a ring we obtain rings of different sizes and scales.

Furthermore, reverse engineering is used for the generation of custom fits to human surfaces and for mating parts [18]. Examples of such applications are custom helmets, space suits and prosthetic parts. Another example is described in [1], where generic models of mannequin torsos are fit to 3D point clouds of human torsos for garment modeling applications.

Finally, reverse engineering techniques are often applied to medicine and animation. An example of a medical application is the creation of bone pieces to be used in orthopedic surgery for the substitution of a shattered bone. The bone supplement is reverse engineered to exactly fit with the neighboring bones for a specific human. In animation, a prototype of a character is drafted, scanned, recreated from the 3D point cloud and finally used in an animated sequence.

### 3. CAD MODELS FOR REVERSE ENGINEERING

Reverse engineering results in the creation of CAD models of existing objects. The more information a CAD model contains and provides the better, especially in cases of applications that demand accuracy and robustness. An appropriate CAD model should be able to capture design intent. A means to achieve this is by providing for parameterization of dimensions and tolerances and definition of constraints. Besides, a usable model doesn't necessarily result from exact interpolation of the 3D point cloud, but usually results from suitable approximations, since the point cloud usually contains noisy data.

Some of the most often encountered CAD representation models are: point clouds, meshes, boundary representations (B-reps), constructive solid geometry (CSG) models, spatial partitioning models, and feature-based and constraint-based models.

**Point Cloud:** The point cloud is the collection of 3D points that are acquired during the scanning phase of reverse engineering process, and it is the initially obtained representation of the object. The point cloud describes the object without providing any information about the connectivity of the points, the geometry of the object or the design intent. Therefore this type of representation model is inappropriate for applications where

editability is required. Such representations are also usually costly in reference to system resources.

**Meshes:** Meshes (e.g. polygons or triangles) lead to the creation of models that conform to the original physical object. However, meshes that perfectly interpolate the 3D point cloud or that approximate the surfaces of the data do not capture design semantics, such as design intent, functionality and behavior. Therefore, this type of model representation is not appropriate for objects with specific conceptual design and functionality, such as mechanical and industrial parts.

Polygonal meshes are usually not appropriate to describe complex and detailed objects. In this case, a large number of polygons are needed to sufficiently approximate the initial object and this is costly both time-wise and space-wise. Also, arbitrary shape manipulation is not efficient when the object is represented with polygonal meshes. The creation of accurate models is extremely difficult, especially when the object is small and complex, such as jewellery.

This type of representation is usually used for machine representations and rendering, not for user-controlled modifications. Very often another model representation is used to modify the object and meshes are used to render it.

**Boundary Representations (Breps):** Boundary representation models describe an object with edges and facets with specific orientations. This type of model can give either an exact or approximate representation of an object. It is the representation that follows the point cloud phase during reverse engineering. Many algorithms have been developed for creating a boundary representation model from a 3D point cloud [3]. A Brep model may be constructed using NURBS (Non-Uniform Rational B-splines) [11, 15] or other BSpline patches. This type of representation is useful in applications where free-form surfaces are part of the repertoire of primitives.

B-rep models are useful for representing any type of object, such as mechanical parts and objects of aesthetic design. Surfaces can be described using appropriate parametric representations. However, spline patches, and generic B-rep models, do not capture design aspects of the object that refer to functionality and relationships. Therefore, the information provided through this type of model is limited and does not provide tools for modifying parts of the model that affect the whole object (usually editing of local features is feasible by interactively placing control points). B-rep models are fundamental representations which can be used in combination with other elements (e.g. features) to achieve more flexible and useful models.

**CSG:** Constructive Solid Geometry (CSG) models are created by performing Boolean operations on solid primitives e.g. spheres, cones, cylinders and cubes. From this definition we can perceive that CSG models can only represent objects that can be created from solid primitives, therefore this occludes the representation of free-form surfaces and objects. In general, the CSG model representation can be used in mechanical part engineering and manufacturing applications or in other applications where the design history of the objects can be

recorded as a sequence of Boolean operations on geometric primitives. More abstract jewellery designs or decorative objects cannot be represented by this type of models. Modifying CSG models is extremely difficult and therefore a more convenient representation model for complex objects is a combination of CSG and boundary representation models.

**Spatial Partitioning models:** These models result from dividing the object space into voxels. The spatial partitioning can be done uniformly or in the form of an octree.

**Voxel-based/ Volume Models:** Another form of model that can be used in reverse engineering is the voxel-based model. The object being reverse engineered does not pass through the 3D point cloud phase, but is initially represented directly as a volume model made up of voxels. These models are can be created using haptic shape modeling techniques such as in [22, 23]. In this work, the object is “traced” using a spatial position tracker and the object is “cut out” of virtual clay. The model produced is a solid volume representation of the object. This solid model can be turned into a surface model representation using isosurface extraction algorithms. This approach to reverse engineering is useful for avoiding the 3D point cloud data phase, which is cumbersome because of the need to remove noise, and for creating robust models. However, it is an approach feasible only in the case where we can come into contact with the object being scanned and our probe is appropriate for the level of complexity of the object.

Voxel-based representations are useful in representing solid objects, because they provide information about the volume properties of the object. However, much like CSG models, they are not appropriate for object models that are to be modified or manufactured because they are not “flexible”. Changes to specific parts of the model cannot be carried out unless the model is transformed into a surface model first. Also, relationships between parts of the object are not defined, nor is it clear how each part is connected to others. Voxel-based models are useful if they are combined with features and constraint properties.

**Feature-based/Constraint-based Models:** This type of model representation is known to be appropriate for manufacturing of mechanical parts, where there is a well defined relationships among the different elements of the model [2]. Also, feature-based models are ideal for industrial design and manufacturing since the model can be easily modified. This is due to the knowledge provided by the model concerning tolerances, constraints, relationships and connectivity among the features [4][7].

Feature-based and constraint-based methods are often characterized also as knowledge-based. Their main objective is to exploit any knowledge and information that is connected to design intent, functionality and construction process of the object being re-engineered. As stated in [21], it is useful to exploit the design intent and feature relationships that exist in models created for industrial use because they justify some of the attributes of the object that might look like they make no sense. These elements are exploited through the usage of geometric constraints.

There have been many projects that have focused on this type of method. First of all, the REFAB project [10, 12, 16, 17] uses a feature-based and constraint-based method to reverse engineer mechanical parts. REFAB is a human interactive system where the 3D point cloud is presented to the user, and the user selects from a list a feature that exists in the cloud, specifies with the mouse the approximate location of the feature in the point cloud, and the system then fits the specified feature to the actual point cloud data using a least square means method iteratively. The authors give emphasis on the fitting of pockets, where the user draws a profile of the pocket on the point cloud and the system then fits the profile to the data and the profile is then extruded to create the pocket. This feature-fitting process is made more accurate by using constraints that are detected by the system, verified by the user and then exploited to achieve a better fitting of the features to the data. The system supports constraints such as parallelism, concentricity, perpendicularity and symmetry. The constraints defined and used in REFAB look to reduce the degrees of freedom associated with the object as much as possible, so as to obtain high precision models efficiently.

A feature-based reverse engineering method was also used by Au et. al [1] for reverse engineering a mannequin for garment design. The basic idea of this method is to create a generic mannequin model of a human torso, which is appropriately aligned with the 3D point cloud of the desired human torso model, and the generic model is “fitted” to the point cloud by matching up characteristic points of the models e.g. peaks. This method creates parameterized models by exploiting the features of the object and by using them to constrain the fitting process.

This method is an automated approach to reverse engineering human torsos (at the time of the paper, only the matching of critical points is done manually, even though it can be automated). It creates parameterized models with good accuracy. However, it is difficult to apply for reverse engineering any type of jewellery because of the variety of free form designs. If the type of jewellery being reverse engineered is of a specific type, with specific features, then this method could possibly be very useful.

In [6] another approach to reverse engineering is presented in which a priori knowledge is applied and expressed through constraints. This work mainly focuses on determining a set of regularities, and from this set choosing the subset of regularities that best fit the problem and that are consistent between each other. This is also the aim of the work done by Langbein et al [9], where consistent regularities are detected for the beautification of the object that are reverse engineered.

The main focus in all of the above works is to exploit any knowledge that is available about the initial object and the parameters, features and constraints that it contains. By using this information we can more efficiently create and manipulate part characteristics so as modify and create more advanced models.

## 4. USING FEATURE-BASED AND CONSTRAINT-BASED CAD MODELS FOR REENGINEERING JEWELLERY

Jewellery design falls under the category of conceptual and decorative design. We distinguish two categories of jewellery: free form jewellery and jewellery that conforms to certain patterns and constraints e.g. repeated patterns or specific gem cuts. Reengineering of objects that fall under the first category is inherently difficult to automate, whereas the second type of jewellery can be approached using combinations of voxel-based and feature-based techniques.

Reverse engineering jewellery requires that the CAD models created are accurate and robust. These models should be parameterizable to support custom jewellery design. Furthermore, user-designers should have the capability to modify the reengineered CAD model according to their preferences, to create novel designs. For instance, in the case where a ring is reengineered, we would like to be able to modify its dimensions to produce rings of larger sizes, or we would like to be able to extract certain parts of the object to use them to create other pieces of jewellery as set pieces, e.g. a matching set of earrings. To this end, one needs to exploit the features of the original jewellery model and the relationships and constraints that hold between them. By applying constraints and by fitting features to the point cloud we can enrich the semantics model and achieve better accuracy and parameterization.

It is difficult, ambiguous and of questionable usefulness to develop fully automated reverse engineering systems where there is no human intervention. For reverse engineering of jewellery we choose to develop design systems where the user interacts with the system and provides information that can be used to acquire a more accurate and complete CAD representation of the object. Our goal is to make the system as automated as possible, by minimizing user interaction, without sacrificing real time response and high accuracy. This approach has been adopted by many reverse engineering systems [6, 17].

Most work in the literature refers to reverse engineering of mechanical parts and objects of industrial design. In [8] Kai et al develop a reverse engineering system for reengineering rings. A 3D point cloud is generated from the coordinates captured from a CMM (co-ordinate measuring machine) system and the CATIA CAD system is employed to interactively concatenate the points to obtain curves that fit the data. From these (polynomial) curves surface patches are constructed, and these surfaces are then used to generate a Brep representation of a solid model. This method creates basic generic models of the initial ring object. Then, in order to manufacture the ring, the 3D model is transformed into a 2D representation on which the engraving of the ring design will be performed. The authors use radial and planar cuts to obtain the flat representation of the ring.

This method is appropriate for creating blank generic models of rings that a designer will then use to create his/her own ring model. The system also offers a library of precious stones and popular ring settings that the designer can use. However, this is not a complete reverse engineering process in the sense that the

system basically creates blanks on which engraving is performed based on designers' sketches. This method is not useful in the case where sketches are not available.

In jewellery reengineering human interaction is important for creating accurate and robust copies of the initial object, because of the variety of geometric and free form shapes and designs that may be represented on pieces of jewellery. The need for human interaction in the reverse engineering process is also stressed in [6, 17].

By observing different pieces of jewellery we conclude that often there are symmetries present in the object. These symmetries may concern either the whole piece of jewellery, or local areas. These symmetries can be exploited to produce more accurate and robust models and to reduce the time needed to reengineer the initial model.

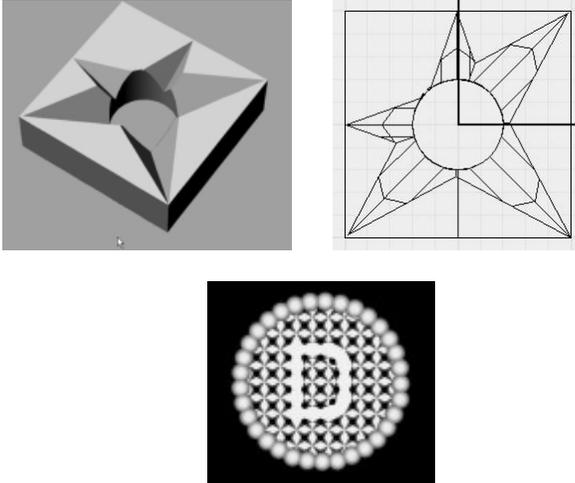
The aim of our work is to create robust CAD models from 3D point clouds of jewellery. We don't necessarily intend to create exact replicas of the original piece. Our goal is to create models resembling the original piece, and that are fully parameterizable and robust, so that they can be modified and manufactured. We propose a method based on extracting the skeleton of the point cloud and detecting some initial features and constraints. These features and constraints are then used in an iterative user-interactive process where the user defines features and constraints that are then fitted to the point cloud. The features are expressed using voxel inspired elements that are combined together to form more complex shapes.

### 4.1 A Feature-based Voxel Inspired Approach to Reconstructing Jewellery

Jewellery can be either very simple solid objects, or objects of more complex craftsmanship. We suggest a feature and voxel based approach to reconstructing jewellery, through the definition of elementary structural elements with specific attributes and properties. These voxel-based elements are used as building blocks to construct more complex shapes and designs. Each voxel-based element has features that make it differ from other elements, for example, a through hole, a pocket, a component forming an angle etc. By changing the parameters of the element we can modify it to obtain a matching piece for the piece jewellery that is being reconstructed. Each voxel-based element also has a set of constraints that refer to its morphology, dimensions and behavior, in reference to itself and to other elements. The voxel-based elements are configured and combined using boolean operations and transformations so as to create the CAD model.

An example of such a feature-based and voxel-based approach is presented in [14], in the case of traditional pierced Byzantine jewellery. In this case, we want to reproduce pierced jewellery, which are jewellery representing designs created by combinations of through holes and carvings around the holes. We consider voxel-based elements called "poxels (pierced voxels)" as the building blocks for creating this type of jewellery. A poxel is a solid rectangular parallelepiped containing a through hole and carvings around the hole. The number of carvings and their directions are what makes each poxel differ from the next. Poxels

are placed side-by-side and unioned together so as to create more complex pierced designs and shapes (Figure 1). By combining pixels we create pierced plates that are then manipulated, transformed and deformed to create specific forms of jewellery. For instance, in the case of a ring, the pierced plate is created and bended along a circular curve.



**Figure 1 - (left) A "poxel", (right) a wireframe representation of a poxel and (middle) pierced jewellery.**

## 4.2 Extracting Skeletons from Point Clouds

Our approach to reverse engineering jewellery takes as input a 3D point cloud, which has been processed, and possibly noisy data has been removed. We wish to obtain information from the 3D cloud data regarding the topology of shapes that exist in the initial object that has been scanned. This topological information is subsequently used to obtain knowledge regarding the morphology of the piece of jewellery that is to be reengineered. For instance, it is useful to detect that the point cloud is “built” on or around a large flat surface, because this indicates that this piece of jewellery is not a ring or a bracelet. Also, by looking at the dimensional parameters of the data set we can make a more specific hypothesis concerning the type of jewellery that the point cloud corresponds to.

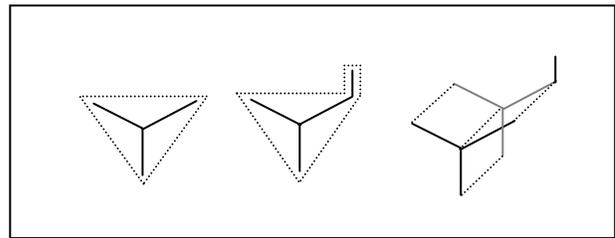
We acquire this knowledge by using a method to detect and interpret the curves of symmetry that exist in the object. We start off by examining cross-sections of the point cloud and by determining the 2D medial axis of each cross-section. The medial axis of a two dimensional shape is the closure of the locus of the centers of all maximal inscribed discs [20]. The symmetries of an object are reflected through its medial axis. We detect the medial axis of each cross section and then interpolate these medial axes to create the 3D skeleton of the point cloud.

More specifically, we examine cross-sections in pairs. We compare the medial axis of each cross-section with the next and we determine whether they are identical or almost identical. In the case where they are identical, we interpolate the axis by connecting corresponding points and by creating connected surfaces. If the medial axis transformations differ (using a point

set distance) over a threshold (which is set using some experimentally determined measures of the point cloud), then we consider a new cross-section in the middle of these two, and after computing its medial axis, we compare it with the previous cross-sections. This process is iteratively carried out until the whole point cloud is scanned and the skeleton of the object is determined.

Many methods have been proposed for computing the 3D skeleton of an object, such as [5]. However, we are not interested in exactly computing the skeleton. We use an appropriate approximation of the skeleton that captures sufficiently the general shape of the object. Computing this approximate skeleton is useful in the following steps of the method, where feature and constraint fitting is carried out. The skeleton assists the automatic feature and constraint detection phase. For instance, if the skeleton contains points that branch out and are end points, then we can assume that the shape contains some sort of end point/angle at that location. In Figure 2 (left) the left branch of a truncated medial axis corresponds to a sharp angle in the object form. Conclusions about the shape morphology can also be derived from the angles that are formed between the branches of the medial axis.

Another example of the usefulness of the skeleton is in the case of a simple cylindrical-shaped ring, the axis of symmetry that corresponds to the ring circumference is a circular surface that is concentric with the circle that coincides with the cross-section of the cylinder. Therefore, generally speaking, if by detecting the symmetry axes in a 3D point cloud we find that one of them is a circular surface that passes through all a large part of the point cloud, then we can hypothesize, along with some other conditions, that the 3D cloud represents a ring, a bracelet.

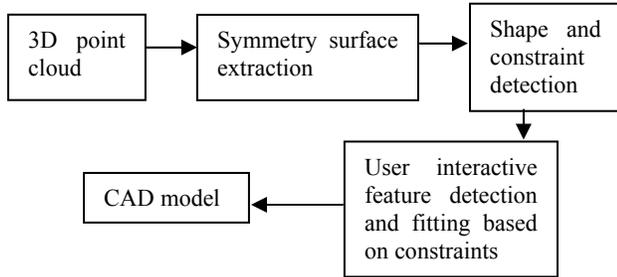


**Figure 2 - (left) a cross-section of the point cloud, (middle) a second cross-section, (right) The skeleton created through interpolation**

## 4.3 Fitting Features and Imposing Constraints

By detecting the type of jewellery represented by the point cloud we then continue building the model by exploiting certain features and constraints that exist. Feature detection and fitting is performed interactively. The 3D point cloud is reverse engineered using a voxel inspired approach, in which each feature is represented and modeled through a voxel-like element. The voxel-like elements are then unioned together to form a solid CAD model in an approach similar to the one followed in [14].

Some constraints are embedded in the system but the user has the ability to define his/her own features [7]. Constraints are defined for the features found on each voxel element and for the relationships among the various voxel-like elements combined together to create the CAD model.



**Figure 3 - A diagram of the feature-based constraint-based method**

We can summarize our approach by the following process:

- i. Consider cross-sections of the point cloud and compute the medial axis of each cross-section. Compare the medial axis between each neighboring cross-section:
  - a. If two medial axes transforms are similar (based on a similarity metric and an experimentally derived threshold), then it is most likely that the surface formed between the two cross-sections is a continuous shape. We then consider a cross-section in between the two former ones, to assure that our assumption is correct. Then we create surfaces that connect the two medial axes by connecting corresponding points of the one medial axis with the other. The corresponding points create surfaces that are fit together. If there are points that are not paired up, then these are connected with points from cross section that will be considered later.
  - b. If the two medial axes are not considered similar enough, then we consider a cross section in-between the two and return to step a.
  - c. When the whole point cloud has been scanned, then the skeleton of the cloud is the union of all the intermediate surfaces that have been computed.
- ii. After the skeleton is extracted, we automatically detect shapes and constraints. From the shape of the skeleton, we can derive information about the shape of the object at branch points of the skeleton. Also, constraints such as perpendicularity and parallelism are automatically inserted. For instance, if we determine that a large portion of the symmetry surface is part of a cylindrical or cylindrical-like surface, then we can assume that the point cloud represents a ring, a bracelet or some other round piece of jewellery with a hole through it. The final

jewellery type is determined based on parameter values and constraints e.g. point cloud size.

- iii. After the feature and constraint extraction is complete, an iterative process is initiated, in which the user points out features in the point cloud and the system fits these features to the cloud with respect to existing constraints. Features are represented through voxel-based elements
- iv. An feature-based, constrained-based, voxel-inspired CAD model is derived.

## 5. CONCLUSIONS

In this paper we considered the different types of CAD models that can be used to represent objects being reverse engineered. We have established that the appropriateness of a model is strongly connected to the type of application it is used for. For jewellery design we have concluded that a feature and constraint based model is most appropriate for representing these types of objects, because of their complexity and design intent capturing necessity.

After taking surveying the different types of reverse engineering methods that have been developed for feature and constraint based applications, we have ascertained that each method covers a specific application domain. Methods that are very efficient for mechanical parts and manufacturing are not as efficient in the case of jewellery design, due to the various free form surfaces, complexity and variety of designs.

To develop CAD jewellery models that are accurate, robust and efficient certain requirements must be taken into consideration. We propose a interactive system which exploits feature and constraint knowledge to create feature and constraint based voxel inspired models that can be prototyped or further modified and adapted to conform with certain requirements or custom orders.

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