A Feature-Based CAD Approach to Jewellery Re-engineering

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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 creating editable CAD models meant for manufacturing we identify that it is more appropriate to use feature-based constraint-based representations, since they capture plausible 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 skeleton construction, feature and constraint information exploitation to obtain a more robust and accurate CAD model. First we automatically construct the skeleton of the point cloud. Constraints are automatically detected based on the skeleton 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, feature-based design, skeleton, CAD, 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 re-engineered. Using CAD models to represent the scanned object is very important in various industries because they help improve the quality and efficiency of design and they also speed up the manufacturing and analysis process [3], [17].

Reverse engineering is widely used for various reasons. First of all, by reverse engineering a part we can obtain the CAD model of a part that is no longer manufactured by its manufacturer or for which only traditional 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 stage. Furthermore, stylists and artists very often create physical models of their concepts by using clay, plaster or wood. These real-scale models should then be used to create CAD models for manufacturing the objects on an industrial scale.

A particularly interesting application of reverse engineering is that of jewellery reconstruction. Jewellery design falls under the category of conceptual and decorative design. In this paper we present a user-interactive feature-based approach to re-engineering jewellery that aims at producing robust and accurate models that can either be manufactured or modified to create new jewellery pieces. Our approach exploits the skeleton of the point cloud to automatically extract features and constraints that exist in the scanned object. Then, an iterative process is carried out, through which the user defines features in the point cloud and the system fits the features according to existing constraints and previously fitted features.

Section 2 presents the advantages of using feature-based models for jewellery re-engineering. Section 3 presents related work jewellery reengineering. Section 4 describes a novel approach to re-engineering jewellery. Section 5 offers conclusions.

2. FEATURE-BASED REVERSE ENGINEERING

A current trend in reverse engineering is the use of feature-based models and methods. Feature-based models are convenient for manufacturing mechanical parts, where there are well defined relationships among the different parts 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 features [4],[18].

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 issues of the object being re-engineered [12]. As reported in [20], it is useful to exploit design intent and feature relationships that exist in models created for industrial use because they justify some of the attributes of the object that are obsolete if they are not related appropriately. Such information may be expressed through the use of geometric constraints.

There have been many projects that have focused on such approaches. The REFAB project [10], [11], [15], [16] 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 predefined list a feature that may exist in the cloud, specifies 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 place emphasis on the fitting of pockets, where the user draws a profile of the pocket on the point cloud and the system 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 aim to reduce the degrees of freedom associated with the object as much as possible, so as to achieve high precision CAD models efficiently.

A feature-based reverse engineering method was also used by Au et. al in [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. This approach creates parameterized models with acceptable accuracy. However, it is difficult to be applied for reverse engineering 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 prove useful.

In [7] 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 describe the problem and that are consistent to each other. This is also the aim of the work done by Langbein et al in [9], where consistent regularities are detected for the beautification of the object that is reverse engineered.

The main focus in all of the above work 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.

3. RE-ENGINEERING JEWELLERY

Jewellery design falls under the category of conceptual and decorative design. We can 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. Re-engineer of objects that fall under the first category is difficult to be automated, 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, the user-designers should have the capability to modify the re-engineered CAD model according to their preferences, to create novel designs. For instance, in the case where a ring is re-engineered, we would like to be able to modify its dimensions to produce rings of larger sizes, or we would like to be able to choose certain parts of the object to use them to create other pieces of jewellery as sets of 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 fitting features to the point cloud we can enhance the semantics model and achieve better accuracy and parameterization.

It is very difficult to develop fully automated reverse engineering systems where there is no human interaction. It is more appropriate to 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 systems, such as [7], [16].

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 re-engineering 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 curves (polynomial curves) surface patches are created, 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, 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, since 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 engineering drawings. This method is not useful in the case where the drawings 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 illustrated on pieces of jewellery. The need for human interaction in the reverse engineering process is also stressed in [7], [16].

By observing different pieces of jewellery we notice that in most cases 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 re-engineer 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 pieces. 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 a 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, as we will see in the following, are represented using voxel-based elements that are combined together to form more complex shapes.

4. A FEATURE-BASED CAD APPROACH TO JEWELLERY REENGINEERING

Our approach to reverse engineering jewellery starts from a 3D point cloud that has been processed and stripped from noisy data. We would like to obtain information from the 3D cloud data about the topology and shapes that exist in the initial object that has been scanned. We intend to achieve this by using a method to detect and interpret the axes of symmetry that exist in the object in order to determine the type of jewellery that is to be reverse engineered. This approach resembles the concept behind the medial axis. A medial axis of a three dimensional shape is the closure of all points that have more than one closest point on the shape boundary [19]. The symmetries of an object are reflected through its medial axis. We are not interested in computing the exact medial axes or all the axes of symmetries, but only those that are useful in determining the general shape of the object. 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 or a large part of the cloud points, then we can conjecture that the 3D cloud represents a ring or a bracelet.

We obtain this knowledge by using a method to detect and interpret the axes of symmetry that exist in the object. From this we determine the type of jewellery that is to be reconstructed. 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 [19]. 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 in order to create the 3D skeleton of the point cloud.

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 medial surface. We define a good approximation of the medial surface to determine the general shape of the object. Computing this approximate skeleton is useful in the subsequent steps of the method, where feature and constraint fitting is carried out. This is because knowledge of the skeleton can assist 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 Fig. 1(left) the left branch of the 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

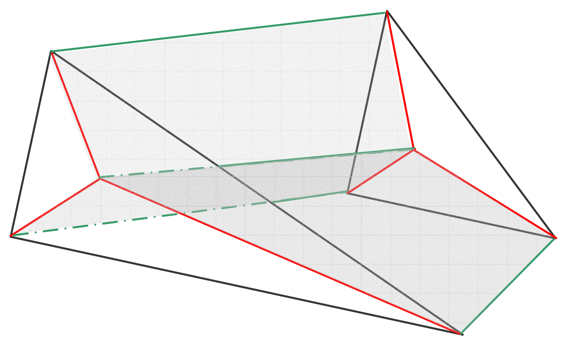

Fig. 1. Two triangular cross-sections, their medial axes (red) and the interpolating edges used to create the medial surface (green)

4.1 Skeleton Construction from the Point Cloud

The skeleton of an object provides information regarding its shape morphology. The skeleton of an object can be used for automatically extracting features and constraints from the point cloud. We present two different approaches to calculating the skeleton of the point cloud depending on the genus of the object, which represents the number of handles that exist in the object.

Initially, we orient the point cloud by placing it in a convenient direction in the coordinate system. We obtain the diameter of the point cloud, i.e. the point pair with the largest Euclidean distance. We place the point cloud in such a way so that the one point of the pair is on the origin of the coordinate system (0, 0, 0) and the other is placed on the z axis. Following this, we find the correct orientation for the point cloud around the z axis. We determine which pair of points, when projected on the xy plane, form the largest distance and rotate the cloud around the z axis until the alignment is such that the largest projection pair is located on the y axis. After this, our point cloud is properly orientated and we create a bounding parallelepiped around point cloud (Fig. 2(d)).

We form a bounding parallelepiped for the point cloud and define a planar surface parallel to the top and bottom surfaces of the bounding parallelepiped. We use this surface to “cut” the point cloud into slices by sweeping it along a path and we examine if each slice contains one “continuous” shape or more. If there is a large “space” between pairs of points then it is very possible that a hole is formed at that location. This can be further looked into by deriving more slices around that area and by examining the formation of the points. If we determine that there is a hole in the point cloud then we can also determine its diameter and consequently its center. If there is a hole present in the point cloud then the object is of genus 1, otherwise it is of genus 0. We are not currently interested in examining genus 2 or more objects, because they can be more simply looked at as combinations of objects of genus 0 and 1.

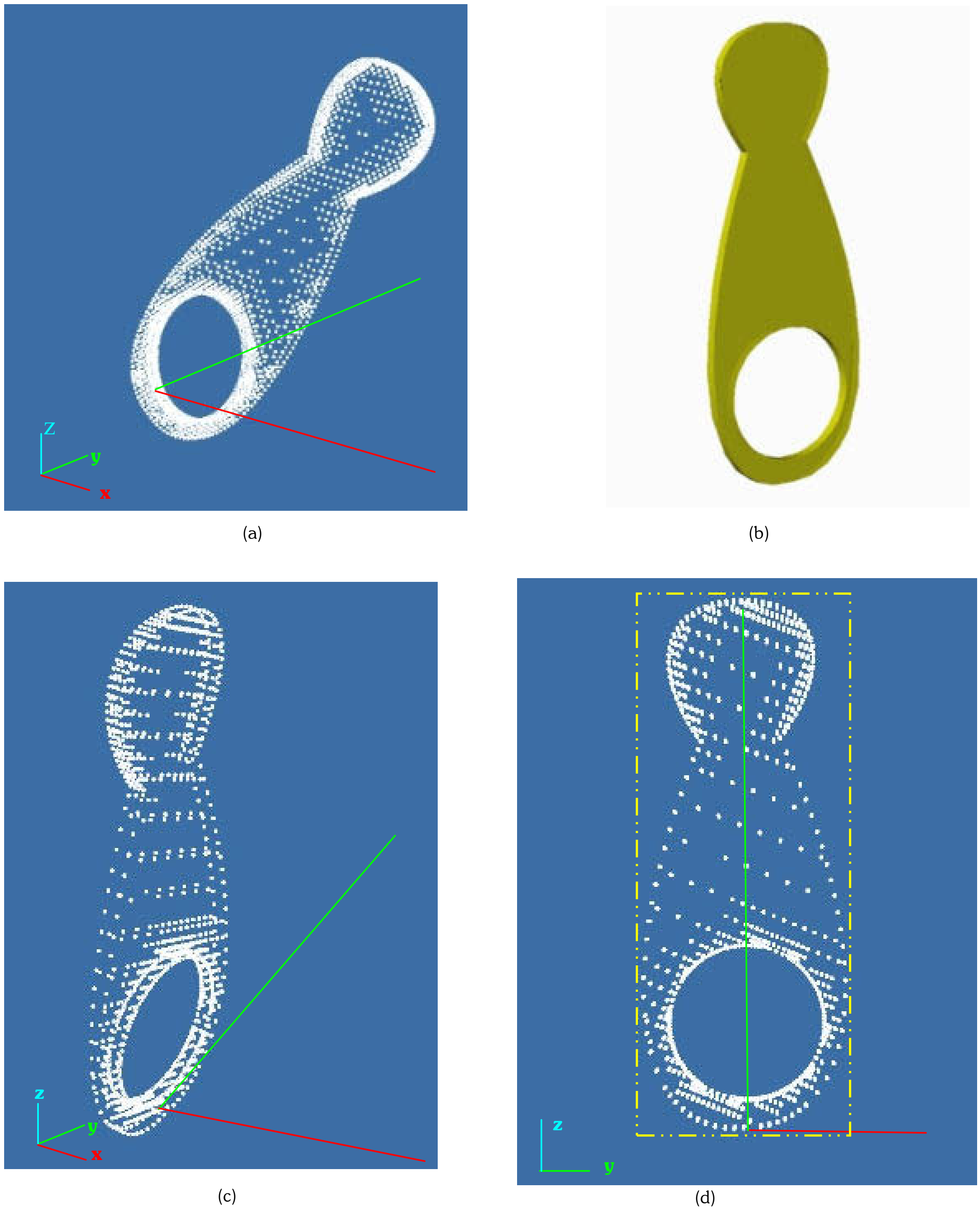

Fig. 2. (a) The point cloud before its reorientation, (b) the object whose point cloud is displayed in (a), (c) the point cloud after it has been reoriented, (d) bounding parallelepiped of the point cloud.

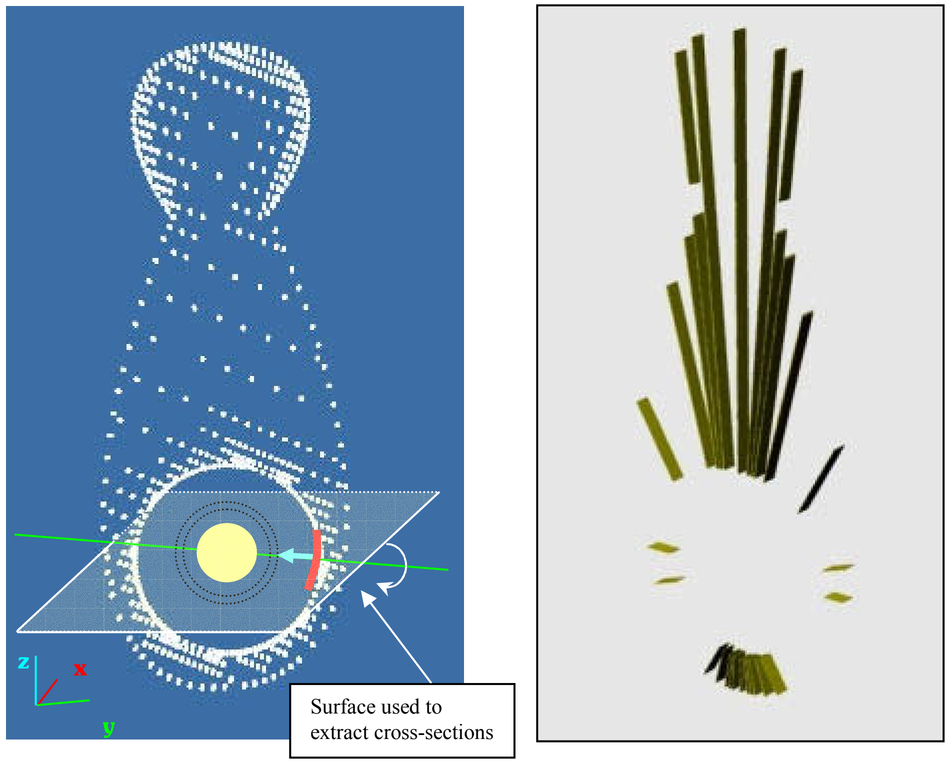

Fig. 3. (left) An example displaying how the sphere is augmented and how the planar surface cuts through the point cloud, (right) an example of the cross-sections obtained from the object by intersecting it with planar surfaces.

After determining the genus of the point cloud, we continue on to construct the skeleton of the object depending on the genus. The skeleton of constructed by combining the medial axes calculated on individual cross-sections of the point cloud. Therefore, it is important to determine a method for deriving the cross-sections of the point cloud that are going to be used for the skeleton construction phase.

In the case that the point cloud is of genus 0, we consider a sphere that is created at the center of the bounding parallelepiped by the intersection of the diagonals of the bounding parallelepiped. We enlarge this sphere until it "touches" a point of the cloud. Around this area we form a local surface and calculate a normal for it. We consider a planar surface that passes through the center of the sphere and contains the normal of the point cloud at the local boundary surface. We then rotate the surface around the center of the sphere and determine the smallest cross-section that is obtained. The smallest cross-section is used as a starting point for "scanning" the point cloud and deriving cross-sections that are to be used in the skeleton construction phase. From the initial cross-section we "walk" on a parallel path to the faces of the bounding parallelepiped.

In the case where the object is of genus 1, then it is best to exploit the knowledge of where the hole in the object is. When determining the genus of the object we obtain information about where in the point cloud the hole is located and which is its diameter and center coordinates. We use the center of the hole to create a sphere which we continuously enlarge until it intersects the point cloud at a certain area of points. At this small surface we consider a normal on the local surface and we create the planar surface that passes through the center of the sphere and contains the normal. The intersection of the surface and the point cloud gives us one of the cross-sections. All other cross-sections are derived by sweeping the surface by angle a around the axis that goes through the center point and is perpendicular to axis z, by which the point cloud was oriented (Fig. 3).

For each cross-section obtained by the above method, we compute the 2D medial axis. Then, we examine the cross-sections in adjacent pairs and compare the medial axis of each cross-section with the next and determine if they are similar enough. In the case where they are similar enough, we interpolate the axes by connecting corresponding points and by creating connecting surfaces. If the medial axes are very different we consider a new cross-section between the 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.

4.2 Fitting Features and Imposing Constraints

By knowing the type of jewellery represented by the point cloud we can then continue building the model by exploiting certain features and constraints that exist. Feature detection and fitting is done in co-operation with the user of the system. The 3D cloud is reverse engineered using a voxel-based approach, in which each feature is represented and modeled through a voxel-based element. Voxel-based elements are used as building blocks to construct more complex shapes and designs by unioning them together to form solid CAD models. 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 an appropriate piece according to the 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 so as to create the CAD model.

An example of such a feature-based and voxel-based approach is presented in [13], [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 named “poxels” as the building blocks for creating this type of jewellery. A poxel is a solid rectangular parallelepiped containing a through hole and carvings. The number of carvings and their directions are what makes each poxel differ from the next. The poxels are placed side-by-side and unioned together so as to create more complex pierced designs and shapes (Fig. 4). By combining poxels we create pierced plates, that are then manipulated and transformed to create specific forms of jewellery. For instance, in the case of a ring, the pierced plate is created and bended along the appropriate axis.

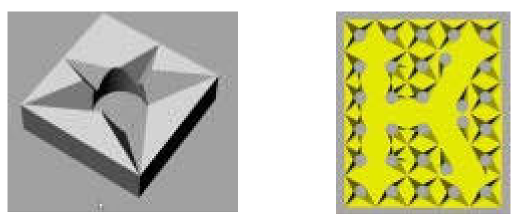

Fig. 4. (left) a pierced voxel, (right) a pierced plate displaying the letter k created by combining pierced voxels

Some constraints are embedded in the system but the user has the ability to define its own features [4]. Constraints are defined for the features found on each voxel element and for the relationships between the various “voxels” combined together to create the CAD model.

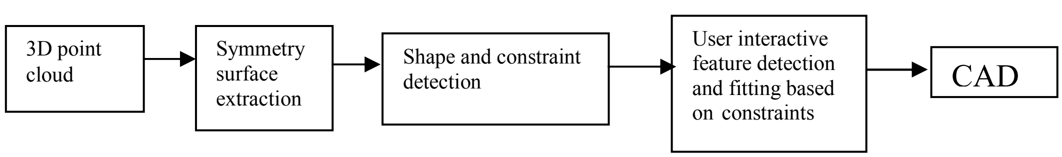

Fig. 5. A diagram of the feature-based constraint-based method

We can summarize our approach in the following algorithm (Fig. 5):

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. A feature-based, constrained-based, voxel-inspired CAD model is derived.

5. CONCLUSIONS

In this paper we presented a feature-based approach to re-engineering jewellery. Reproducing jewellery is a challenge because of the complexity and size of the models. In general, for a reverse engineering system to create CAD jewellery models that are both accurate and robust, certain requirements must be met. We propose an interactive system which exploits feature and constraint knowledge to create feature and constraint based parametric models that can be prototyped or further modified and adapted to conform with certain requirements or desires.

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