A Novel Algorithm for Free-Form Surface Modeling in Product Design and Prototyping

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Track1: Machine Design

A novel algorithm for the free-form surface modeling in product design and prototyping

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Abstract

The product design methodology has undergone rapid changes during the last decade due to developments in different manufacturing technologies like 3D printing/additive manufacturing. However, the design process is still lagging in innovation for new opportunities like medical devices, jewelry design, garment design, etc. The conventional product design approach starts by sketching a planar profile and then sweeping or extruding that 2D profile along a well-defined path. Because of diversified and rapid development in product design, sketching is no more restricted to a planar surface. The custom products like clothing and jewelry often need a non-planer 3D profile or path to be drawn on a free-form object. To the best of our knowledge, there is not much work accomplished to address this design requirement. Even commercial software does not have enough functionality to overcome this limitation. A novel method is presented in this paper to overcome this limitation by utilizing an intermediate representation of the freeform object. For free-form surface modeling, the user can directly draw a 3D profile or path on any arbitrary shape. Results from an implementation tested on various free-form shapes are presented.

Keywords: CAD, Free-form surfaces design, Product Design, Prototyping, Sketching

1. Introduction

Advancements in technologies like additive manufacturing (AM) and 3D scanning are changing how people create and manufacture things. AM's digital to physical approach and 3D scanning of freeform geometry may be coupled to produce anything with any level of customization, allowing goods to be tailored to a specific person or object. Custom items have intrinsic benefits over mass-produced alternatives, such as they can give greater comfort, distinctive and aesthetic appeal, and superior performance. The customers and requirements become more diverse, adding needless expense and complexity to the design process. The diversification leads to the necessity of swiftly and simply developing the complicated forms depending on the customer's need. Freeform surfaces expressly represent custom items, and some existing freeform shapes influence their shapes. With the popularity of low-cost consumer-level 3D scanners such as 3D sense, people may now readily extract 3D forms by reverse engineering. Traditional computer-aided design (CAD) software tools, on the other hand, take a long time to adapt the design to an existing 3D geometry. The quality and effectiveness of these items are determined by how well their forms conform to the reference shapes. For example, an orthosis-based on the anatomical object is shown in Figure 1. For effective results, the orthosis needs to demonstrate the highest conformance with the freeform-shaped anatomical structure of the hand. A set of translation and rotation operations and often shifting views are necessary to assure the design's fitness. The product design starts with modeling the product using CAD software and follows simulation, analysis, CNC programming, 3D printing, etc. It is essential to create the model as accurately as possible. Although modeling software has come a long way, many limitations still need to be addressed.

Figure 1: An upper limb orthosis

Carlo H. Sequin [1] highlighted the boundaries of existing CAD packages in design for aesthetic objects. The user interface is a weak link as it cannot provide complete freedom to users. For example, when one starts with a brand-new concept such as a bridge in the shape of a "Moebius band," the user doesn't know where to start, limiting creativity. It is seen that generally, the CAD software is outdated by up to 20 years concerning the latest research or ideas [2]. A few of the limitations of CAD packages are mentioned below: -

- No support for sketching on freeform surfaces.
- Boolean between multiple bodies simultaneously is not possible in leading CAD packages.
- Mid-surface generation is impossible for free-form and hybrid (solid and surface) bodies.
- Modeling of the porous medium is not possible.
- Impossible to model non-homogenous materials, i.e., varying density, changing composition, and multiple phases (solid-fluid).

Sketching is essential for designing any surface or shape using CAD software. However, in the current CAD software packages, sketching is limited only to planar surfaces, severely restricting the product designer's creativity. Sketching is possible only on planar surfaces, and to get sketches on free-form surfaces like Bezier/B-Spline surfaces, and many workarounds are used. The freeform surfaces are usually the tensor product of NURBS (Non-uniform Rational B Spline) curves. A NURBS curve is defined as

$$C(u) = \frac{\sum_{i=1}^{k} N_{i,n}(u) w_i P_I}{\sum_{j=1}^{k} N_{j,n}(u) w_j} - - - - - - - - (1)$$

Where u is an independent variable, N is the B-spline having k number of control points with n denoting the polynomial degree. The P represents the control point, and w is the weight.

A non-uniform B-Spline surface is defined by equation 2.

$$S(u,v) = \sum_{i-1}^{k} \sum_{j-1}^{l} R_{i,j}(u,v) P_{i,j} - - - - - - - - (2)$$

Where $R_{i,j}$ is a rational basis function defined as

$$R_{i,j}(u,v) = \frac{N_{i,n}(u) N_{j,m}(v) w_{i,j}}{\sum_{p=1}^{k} \sum_{q=1}^{l} N_{p,n}(u) N_{q,m}(v) w_{p,q}}$$

The present commercial software provides a limited workaround for creating a free-form sketch on an arbitrary surface. The workarounds of creating a free-form curve consist of projection, intersection, wrapping for cylindrical surfaces, and curve fitting by picking points on free-form surfaces. But this does not serve the purpose when the geometry of the freeform surface or the required sketch itself is complex. The final profile is usually very much different from the planar sketch created due to the complex shape of the free-form surface. The user must perform several iterations to get the required profile projected for the desired free-form sketch. Hence, the above workaround cannot generate accurate results quickly and efficiently. As shown in Figure 2, the user has created a simple rectangle on a plane, taken at a minimum possible offset distance (i.e., the plane must ultimately lie above the surface). After completing the 2D profile (rectangle) shown in Figure 2a, the user now tries to project the planar profile on the true surface to get the desired output. But when it is projected on true surface, the sketch is broken; moreover, it does not correlate with the 2D sketch that is projected, as shown in Figure 2b. Apart from that, no other conclusion can be drawn about the reason, and a slight change in dimensions of the sketch in the offset plane may give an entirely different output after projection. Also, the above approach is not suitable for surfaces with complex topology.

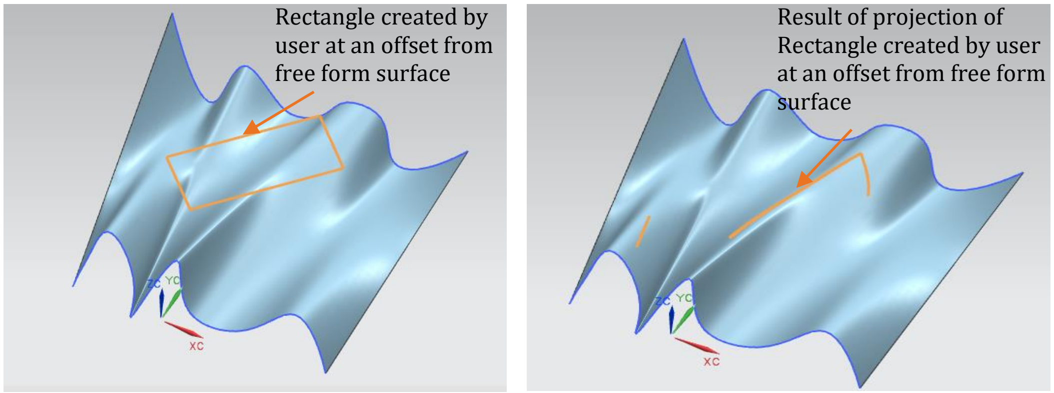
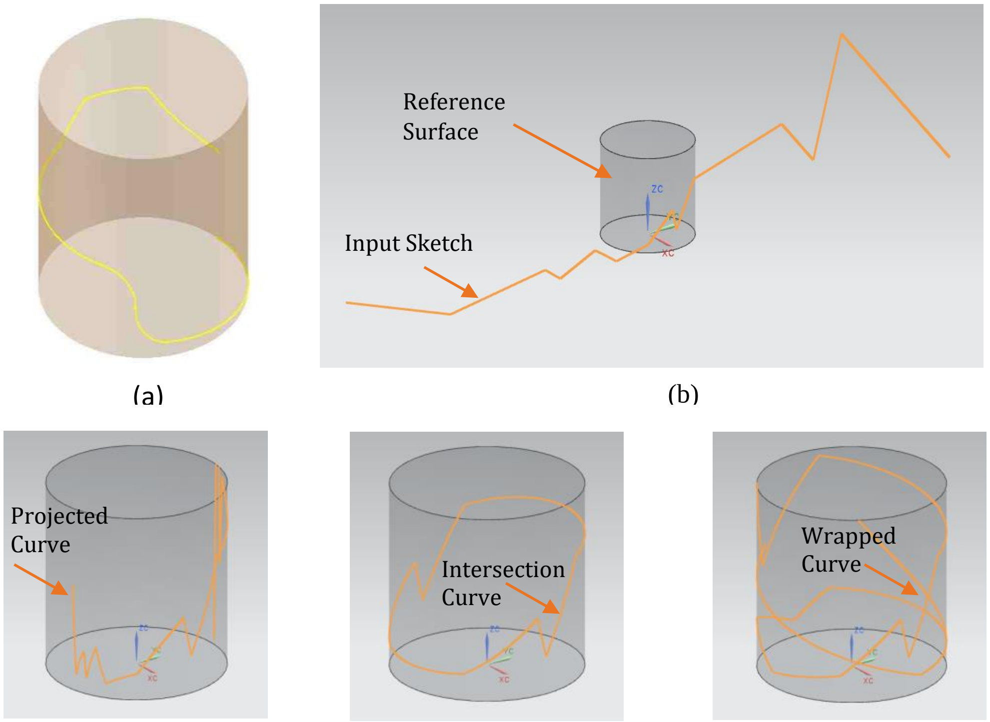


Figure 2: a) Sketch Created by the user on an offset plane b) Sketch after projection on the surface

Furthermore, the present approach also fails to generate the required result in cases where the size of the sketch is larger than the surface on which it needs to be projected. For example, when the user tries to project an ellipse on a torus, projection fails because the sketch size is larger than the surface.

Literature Survey - Over the last decades, many algorithms have been proposed for modeling free-form surfaces. Sweep, extrude, revolve are few of them. Most of them starts with a 2D sketch (drawing). In these methods, users sweep, extrudes, or revolves a planer profile (a 2D sketch on a plane) along a path. Limitation of planer profile is a major drawback in advance design and manufacturing process. Some efforts have been made as a work around to create arbitrary profile by using 2D planer profiles for free-form surface modeling. Most of the above methods are gesture-based, not suitable for product design and manufacturing. Florian Levet et al. [3] have proposed an interactive interface for 3D modelling by using bi-dimensional input 2D sketches combining with gesture grammar. Proposed method gives ambiguous results if input 2D sketches has discontinuity. Method is not suitable in product design. A gesture-based interface is proposed by Seok Hyung and Karan Singh [4] to model 3D curves and surfaces with the help of input planer sketches in orthogonal directions. Approach is not suitable for incorporating into commercial CAD packages because of gesture interface. Jonathan M. Cohen et al. [5] presented an interface for generating 3D curves from input 2D sketches. In this approach, the user sketches an initial 2D curve and then draws the second curve as a shadow of the first curve on an orthogonal plane. Algorithm blends these to curves to get the final 3D curve. User cannot predict the final free-form surface as well as the 3D sketch generated from input planer sketches. A method is proposed by Levent Burak Kara et al. [6] for designing 3D geometry based on input 2D concept sketch and 3D wire template. Algorithm aligned the input 2D sketch with the given 3D wire template. This 2D sketch is further modified by user to get the final 3D shape by modifying the 3D template. Proposed methods have many limitations. Creating the wireframe and 2D sketch of complex shapes is a tedious task. Apart from that placement of concept sketch and wireframe template on existing free-form object is very difficult and not intuitive. Charlie C.L et al. [7] presented an approach for 3D garment design around tessellated 3D human model by using feature lines. These feature lines consist of edges and vertices of triangulated 3D model. Approach works for predefine human features, hence not suitable for design & engineering with arbitrary shapes. An algorithm has been proposed by Pablo Diaz-Gutierrez et al [8] to construct approximate free-form surfaces by fitting network of 3D space curve. These 3D space curves are generated based on minimal curvature projection of 2D sketches on curves or surfaces. As the projection is not unique, generated 3D curves and fitted surfaces are not intuitive. Method may be useful for visualization, but not useful for product design and prototyping because of approximation error. Zhang et al. [9] has introduced a curve drawing method on free-form surface by picking the control point of the underlying spline and interpolating with other four neighbor control points. These interpolated control points are then projected onto the reference surface iteratively. A 3D sketch curve is generated by using these projected points. Proposed methods have many drawbacks. Projected points may not topologically connect other points. Process is not intuitive and final 3D curve may not the expected one.

Although there are some claims of 3D sketching on CAD packages, it is multi-planar sketching, which is simply the addition of 2D sketches, whereas 3D sketching is far from reality. But with changes in consumer markets and less design to market time, it is the need of the hour. Therefore, there is a need of developing an algorithm for sketching on free-form objects that can be incorporated in the existing commercial solutions. This will help to reduce efforts in testing, training in an entirely new system by addressing a limitation of the existing CAD packages. The proposed algorithm for sketching on free-form surfaces starts with approximating the surface with facet representation. The user can sketch on the planar elements of the faceted representation with very high fidelity to the original surface. These sketches are then projected on the true surface to get the final sketch on the free-form surfaces.



(a) (b)

(c) (d) (e)

Figure 3: (a) Model object with a curve for reverse engineering (b) A reference surface with an input sketch, result by (c) Projection (d) Intersection (e) Wrapping

2. Methods

In the proposed algorithm, the user starts by selecting the surface for sketching. The user sets the tolerance values so that all the features are captured in faceted representation in detail, and faceted representation is created.

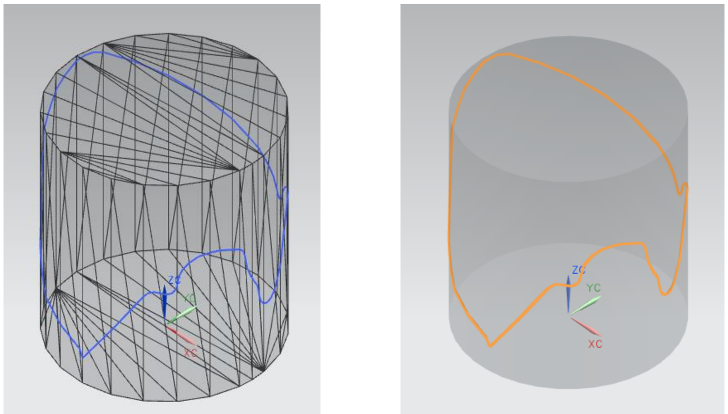


Figure 4: Sketch a) on facet representation b) on the original model

In case the required detail is not present the faceted representation, the user can change the tolerance values to regenerate the faceted representation. The user creates the sketch on this faceted representation as the planar elements in faceted representation allow to do so. After the sketch is completed, the user can project this sketch on the original surface. The benchmark problem chosen to test this algorithm is shown in Figure 3. A 3D sketch is shown in Figure 3(a) is one of the most commonly faced problems in industrial design. This type of sketch is challenging to get using any current workarounds - i.e., intersection, projection, wrap, as explained below. Now user wants a sketch on the surface of the cylinder. To get the same, with the current workarounds, first, it is required to create a sketch on a plane tangent/offset from the surface. After that, the user can choose either projection or intersection to emulate the sketch. Since this is a cylindrical body, another option called wrap is also available. A 2D sketch is created on a plane tangent to the cylindrical surface to be used in present workarounds, as shown in Figure 3(b). As shown in the sketch's output using projection [Figure 3(c)], intersection [Figure 3(d)], and wrapping [Figure 3(e)], the workarounds fail to produce the required sketch on the cylindrical surface. In the projection workaround, the user cannot get any sketch on the opposite side of the projection plane. The projection will result in squeezing the sketch near the object's plane of symmetry. In the intersection, the sketch portion in front of the sketching plane intersects with the surface and gives the output. But it cannot handle the sketch portion outside the object. Wrapping is another option available to emulate sketching of the free-form object, as shown in Figure 3c.

It will wrap the sketch on the body like a screw thread to give the output. Here, no control of the sketch position on the surface is available. It is clear from Figure 3 that the results do not have any proximity with the input sketch from all the three workarounds available. Now we have taken the same model and created a facet representation, and on those facets, the sketch is created as shown in Figure 4a. After creating the sketch on the facets, it is projected on the true model, and the result is shown in Figure 4b. Here, it is clear that the algorithm gives better control than the current workarounds while sketching. It can be used for sketching on free-form surfaces. The following section presents a case study to analyze our algorithm based on the control parameters. The algorithm is tested on a Bezier surface. The results show that the algorithm is successful in generating the outcomes directly which otherwise takes number of iterations in CAD packages. For example, in the case of Bezier surface (Figure 5a), a profile sketch was created on intermediate representation (Figure 5b). The profile sketch was used to create geometric features otherwise not possible like corrugated extruded surface shown in figure (5e) and a sweep feature in figure (5g).

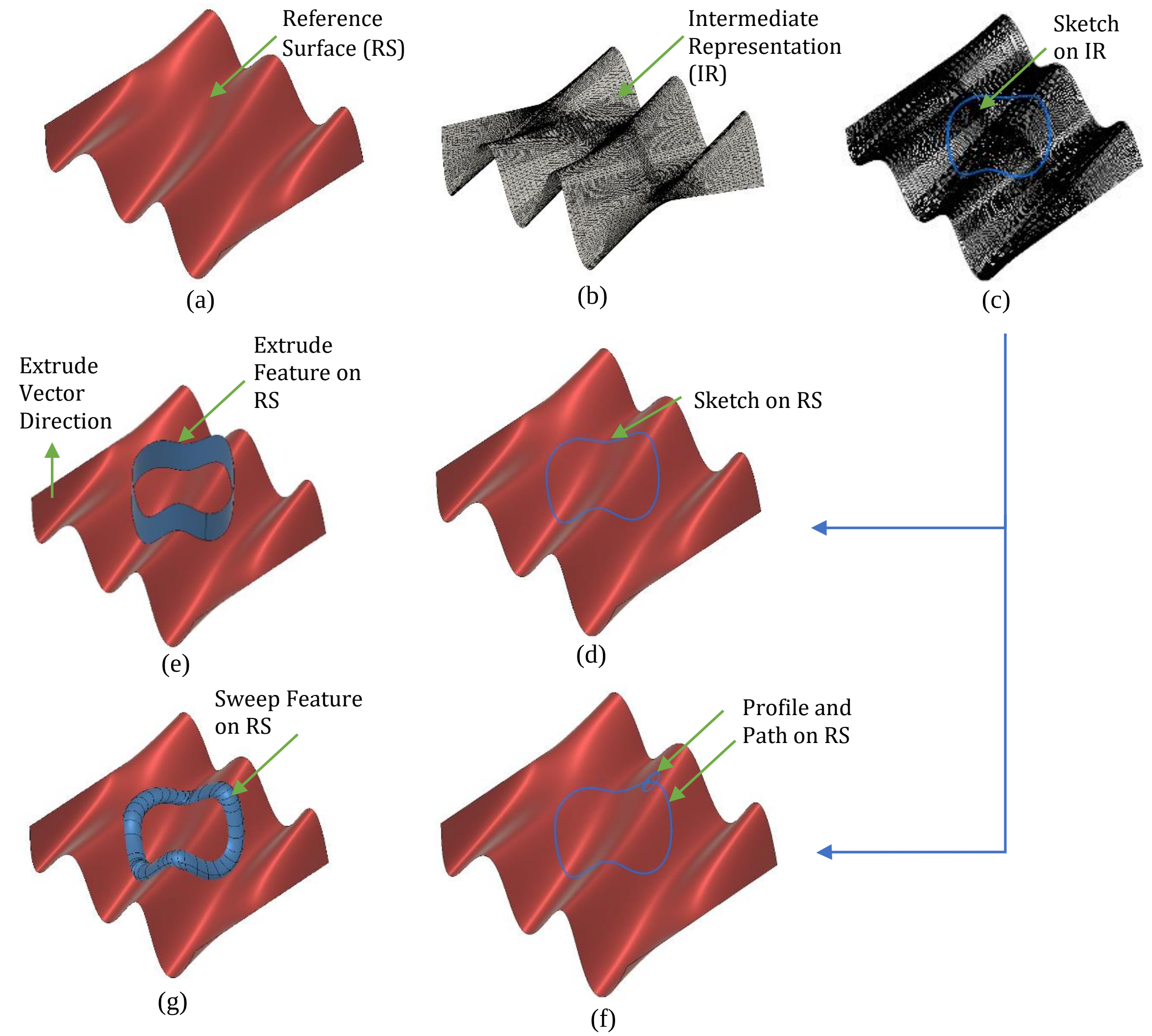


Figure 5:(a) Arbitrary reference surface, (b) intermediate faceted representation of arbitrary object shown in (a), (c) a freeform path is drawn on the intermediate representation (d) sketch is projected on reference surface (e) a free-form object is created by extruding a sketch profile drawn on the reference surface (f) a circular profile created on sketch path (g) a free-form object is created by sweeping a circular profile along the path drawn on the arbitrary reference surface

3. Analysis of effectiveness

Two parameters control the number of facets on a surface while tessellating a surface. These are tolerance and angle deviation. Sketch testing is carried out to analyze the algorithm's effectiveness by varying these two parameters. The line geometries are used to measure the distance. If L and M represent the boundary surfaces of two solids, then the minimum distance is given by

$$d = min_{p \in L, q \in M} ||p - q|| ------(3)$$

If the minimum distance is reached at p and q, the line is normal to both surfaces. In this testing, a sketch generated by the proposed algorithm is compared with an existing sketch. Here, the current sketch is termed a reference sketch. The reference sketch is created by modeling operations in NX® environment on a non-planar surface. The proposed algorithm emulates the reference sketch with various tolerance parameters in this experiment. After that, the deviation for the emulated sketch is measured from the reference sketch. A freeform object created in NX®, as shown in Figure 6, is used for the demonstration.

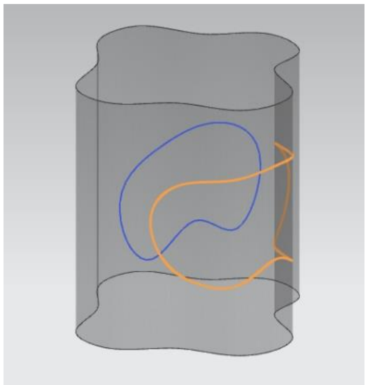


Figure 6: Reference sketch (shown in orange color and emulated from planer sketch shown in blue color)

An input sketch is created on a plane whose normal is the same as the normal at a point on the free-form surface. This sketch is then swept to get an intersection between two bodies.

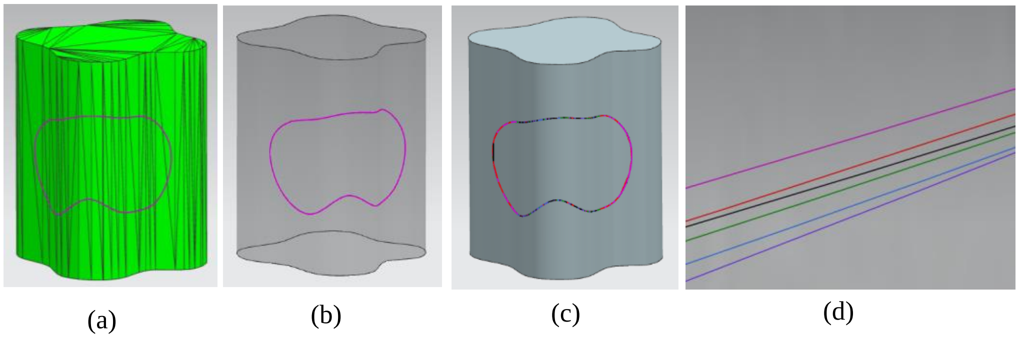


Figure 7: Sketch with tolerance value as one on a) faceted representation b) Freeform surface c) Sketches with different tolerance values b) Zoom-In view of sketches (Reference Sketch-Blue, 0.01- Purple, 0.05- Green, 0.1- Black and 0.5-Red)

This intersection curve represents the reference sketch, as shown in Figure 6. The facets are generated for the same model by setting the value of both the tolerance parameters to 1. The proposed algorithm then emulates the reference sketch on the free-form object by using intermediate faceted representation, as shown in Figure 7(a). The emulated sketch produced by the proposed algorithm is demonstrated on the CAD model in Figure 6(b). Further, 30 equidistant points are created on the reference curve to measure the deviations of the reference curve to the curve generated by the proposed algorithm. The perpendicular distances are calculated by the points on the curve generated by the proposed algorithm. The same experiment is repeated by using facets of different densities created by changing the tolerance value for faceting. Emulated sketches are shown in Figure 6(c) with different colors and zoom-in view [Figure 6(d)]. As shown in Figure 8, the average deviation decreases when we decrease the tolerance value. Another point of interest is the slope of the average deviation curve. As we can see, it is not uniform, whereas, theoretically, it should be. It can be observed that average deviation decreases uniformly when the tolerance value is reduced from 1 to 0.5 and 0.5 to 0.1. But when the tolerance is further reduced from 0.1 to 0.05, the average deviation does not decrease at the same rate. Further lowering the tolerance value from 0.05 to 0.01 gives a meager rate of average deviation decrease.

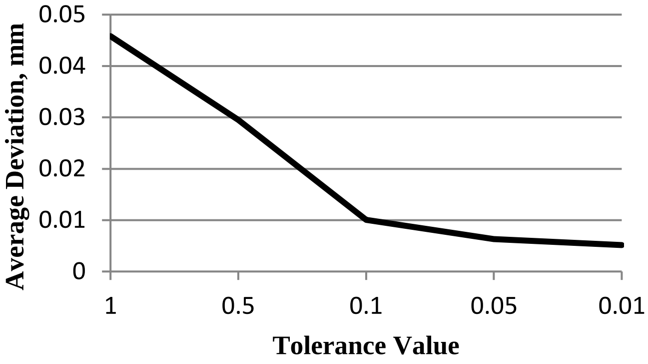


Figure 8: Average deviation for different tolerance values

4. Conclusions

An algorithm is proposed for sketching on free-form objects. It is implemented and tested by using CAD models with freeform surfaces. It is shown with a benchmark problem that the algorithm gives better control and much better results compared to the present workarounds while sketching on free-form objects. Apart from this, extensive case studies are presented to demonstrate the algorithm's robustness further. Unlike the current workarounds, the proposed algorithm shows a high fidelity between input and final sketch. From the analysis of the algorithm's effectiveness, it is established very clearly that the algorithm's accuracy can be increased by increasing the number of facets in the intermediate representation. Tolerance parameters necessary to create the facets play a significant role in sketching accuracy. Our future work is concentrated towards another algorithm that can make faceted representation around the point which the user selects to use as the start point of the sketch and propagate the facet creation in the direction of sketch creation dynamically. Another improvement area is developing the real-time projection of sketch created on the faceted representation to the true surface.

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